IN-39
120878
P-87

NASA Technical Memorandum 107681

A STATE-OF-THE-ART ASSESSMENT OF ACTIVE STRUCTURES

Active Structures Technical Committee

September 1992

(NASA-TM-107681) A STATE-OF-THE-ART ASSESSMENT OF ACTIVE STRUCTURES (NASA) 87 p

N92-33580

Unclas

G3/39 0120878

National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23665-5225

Preface

This report is prepared by the Active Structures Technical Committee of the NASA Langley Research Center. The committee reports to Dr. Michael F. Card, Chief Scientist at the Center. Members of the committee are:

Dr. Harry F. Benz
Dr. John D. Buckley
Mike C. Fox
Jennifer Heeg
Dr. C. Garnett Horner, chairperson
Dr. Seun K. Kahng
Henry L. Kelley
Charles J. Magurany
W. Hewitt Phillips
Dr. Robert S. Rogowski
Richard J. Silcox

Contents

Executive Summary

Many types of smart materials and applications for potential use in aircraft and spacecraft have been examined. It is the opinion of this committee that aircraft and spacecraft performance can be improved by incorporating the use of these materials into their design. Before these materials are more widely accepted by designers of commercial and flight vehicles, more research in the testing and evaluation of these materials is needed.

The essence of this report is captured in the following list of recommendations which cover; actuation materials, smart sensors, information management, applications and research environment.

Actuation Materials

- Langley should focus on the integration of smart materials (piezoceramics, magnetostrictors, and shape memory alloys) into concepts with composites which ultimately will improve vehicle performance and reliability while decreasing fabrication costs.

- Capability, limiting performance, and design approaches of smart materials should be better understood.

Smart/Intelligent Sensors

- Micro-sensors with built-in processors for aircraft and spacecraft applications should be further developed.

Information Management

- A concept for a network that supports multiple smart subsystems and includes processing (either centrally or distributed) for improved vehicle performance and reliability needs attention.

Applications

- More areas of potential use of smart materials for improving aircraft and spacecraft performance needs encouragement. These are ideas that are hidden within the minds of researchers at Langley and it is hoped that the proper stimulants will bring forth these innovations.

Research Environment

- Build upon Langley's capability in materials and structural dynamics modeling and promote cross-directorate communications of research activities.

Acronyms

ACESA	Advanced composites with embedded sensors and actuators
AHS	American Helicopter Society
AIAA	American Institute of Aeronautics and Astronautics
ANN	Artificial neural network
ASAC	Active structural acoustic control
ASC	American Society for Composites
ASCE	American Society of Civil Engineers
ASIC	Application specific integrated circuit
ASME	American Society of Mechanical Engineers
ASSP	Acoustics, Speech and Signal Processing
CMOS	Complementary metal oxide silicon
CPU	Central processing unit
CSI	Control Structure Integration
DARPA	Defense advanced research projects agency
DoD	Department of Defense
DSP	Digital signal processor
ER	Electro-rheological
FEA	Finite element analysis
FIR	Finite impulse response
FTIR	Fourier transform infrared
ICASE	Institute for Computer Applications in Science and Engineering
IEEE	Institute of Electrical and Electronic Engineers
IIR	Infinite impulse response
IOFDR	Incoherent optical frequency domain reflectometry
LMS	Least mean square
LQG	Linear quadratic Gaussian
LQR	Linear quadratic regulator
MCM	Multiple chip module
MIMO	Multi-input multi-output
MIT	Mass. Institute of Technology
MOSFET	Metal oxide silicon field effect transistor
MSME	Masters of Science in Mechanical Engineering
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NASTRAN	NASA structural analysis
NDE	Non-destructive evaluation
NDT	Non-destructive testing
NRL	Naval Research Laboratory
ONR	Office of Naval Research
OTDR	Optical time domain reflectometry
PE	Piezoelectric
PMN	Lead metaniobate
PVDF	Polyvinylidene fluoride

PVF2	Polyvinylidene fluoride
PZT	Lead-zirconate-titanate
RF	Radio frequency
SAMPE	Society for Advanced Materials and Process Engineering
SBIR	Small business innovation research
SDIO	Strategic Defense Initiative Office
SDM	Structures, Structural Dynamics and Materials
SERC	Space and Engineering Research Center
SMA	Shape memory alloy
SPIE	Society of Photo-Optical Instrumentation Engineers
TRW	Thompson-Ramo-Woolridge
VG	Velocity and acceleration
VGH	Velocity, acceleration, and altitude
VLSI	Very large scale integration
VPI&SU	Virginia Polytechnic Institute and State University

1 Introduction

This report is a state-of-the-art assessment of active structures authored by the members of the active structures technical committee. The emphasis in this assessment was towards the applications in aeronautics and space. It is felt that since this technology area is growing at such a rapid pace in many different disciplines, it is not feasible to cover all of the current research but only the relevant work as relates to aeronautics and space.

Before discussing further the subject of active structures, this committee has adopted the terminology as depicted in Appendix A. Domain A contains all structures that have a sensory system. So that in addition to the usual load carrying capability of a structure, the structure also contains some type of sensory system that could be either integrated into the structural material or added on to the structure as a separate sensor.

Next, we define a B domain of structures that contain an actuation function in addition to the load carrying capability. These structure types are called adaptive because they are changeable in a predictable way. Again the actuation function may be contained within the material of the structure or it may be some attached actuator.

The intersection of the A and B domains contains three types of structures. Domain C is the type of structures that have attached sensors, actuators and processors. Examples of a class C system would be a structure with attached accelerometers, attached thrusters or proof mass actuators and an attached processor. As you go from class C to D to E, the degree of integration of the sensor and actuator with the structural material increases. An example of a type D structure would be a truss mechanism with variable length struts. These variable length struts could be hydraulically actuated or ball screw actuated telescoping cylinders. An example of a type E structure might be a structural composite material with embedded piezoelectric ceramic powder. An application of these embedded materials could be for flutter suppression in an aircraft wing or for vibration suppression in a truss strut.

At this time it does not appear that the technology exists to embed processors into structural materials. The silicon median that constitutes the processor is brittle and not compatible with the flexibility and toughness of current structural composites.

This report covers research in smart actuation materials, smart sensors, control of smart/intelligent structures. In smart actuation materials, piezoelectric, magnetostrictive, shape memory, electrorheological, and electrostrictive materials are covered. For sensory materials, fiber optics, dielectric loss, and piezoelectric sensors are examined. Applications of embedded sensors and smart sensors are discussed.

In chapter 4, control approaches for smart structures are discussed and in chapter 5, recommendations for future research are given.

2 *Actuation Materials*

2.1 Piezoelectric Materials

2.1.1 Benefits and Drawbacks

Piezoelectricity is the ability of a material to develop an electrical charge when subjected to a mechanical strain. The converse piezoelectric effect, the development of mechanical strain when subjected to an electrical field, can be utilized to actuate a structure. A local strain is produced in the structure which induces forces and moments. Thus, actuation of a structure may be accomplished at the material level. Lead-zirconate-titanate (PZT) is a piezoelectric ceramic in which the electric sub-domains have been aligned using a very large electric field. Strain is linearly proportional to the electric field in a fully poled piezoelectric material which means that the piezoelectric coefficient is a constant and cannot be electrically tuned with a bias field (see Appendix B for further discussion of piezoelectric materials).

Choosing the proper piezoelectric material to use for a given application is based on stiffness properties, flexibility, electromechanical coupling coefficients and limits on applied voltage. A piezoelectric material's ability to actuate a structure is a function of its stiffness, the limit on the voltage which can be applied, and the electro-mechanical coupling coefficients. Polymers have high voltage limits, yet they have low stiffness and low electromechanical coupling coefficients. Ceramics on the other hand are much stiffer and have large coupling coefficients and are thus better-suited for actuator applications.

Low density and stiffness have, in most cases, prevented the serious consideration of piezoelectric polymers for use as actuators. Ceramics have sufficiently high electromechanical coupling and stiffness that they lend themselves better to actuation applications.

2.1.2 Configurations

2.1.2.1 Bimorph Bender Element

Piezoelectric plates can be configured in different ways to accentuate the displacements or forces being generated. The in-plane expansion and contraction of adaptive materials may be utilized by bonding actuating plates to either side of a center shim. One is expanded and one is contracted; the net result is a bending displacement much greater than the length deformation of either of the two layers. This configuration, which takes advantage of the d_{31} effect (see Appendix B), is referred to as a bimorph or a bender element.

2.1.2.2 Out-of-Plane or Monomorph Element

The intended application may suggest creative configurations for these materials. Designs for out-of-plane displacement actuators have been evaluated. Utilizing the piezoelectrics in monolithic modes, a high stiffness is achieved, however, the displacement achieved is very small. Composite structures have also been evaluated, which produced significantly more displacement, but were less stiff than the monolithic configurations. One of these utilized only the out-of-plane displacement of the piezoelectric. The second utilized both the out-of-plane and the in-plane displacements of the piezoelectric disc. This is the moonie configuration which is discussed in Reference [13]. Bender configurations have also been examined. In one instance, the bender elements were constrained at the periphery of the disc and allowed to operate as an oil can does to achieve the out-of-plane displacements. The stiffness of the configuration was lessened, but more significant displacement results were obtained. Bimorph benders have been found to be 10 times more effective than monomorph benders.

2.1.2.3 Discretely Attached Elements

In structural control, induced strain actuators are utilized generally by bonding them or embedding them in a structure. With these configurations used for inducing flexure, the developed in-plane force contributes indirectly through a locally-generated moment; control authority is thus limited by actuator offset distance. These actuators deform along with the structure. By attaching strain actuators to the structure only at discrete points, as opposed to being bonded or embedded, they are free to deform independently from the structure. The in-plane force of the actuator results in an additional moment on the structure and enhanced control [18].

2.1.3 Piezoelectric Composites

By incorporating piezoelectric rods into a composite material, directional actuation can be achieved with reduced weight. Assuming that the matrix is dielectric, and aligning the 1-direction of the PZT with the fiber direction and the 3-direction perpendicular to the direction of the ply (see Appendix B), and a 65% fiber volume fraction: the elastic properties are similar to a glass/matrix unidirectional fibrous composite. The density is reduced from the monolithic PZT but still twice that of aluminum. The anisotropy of the electromagnetic coupling provides for shear strain actuation through proper ply orientation [1]. Application of this configuration could include actuation of an adaptive wing (i.e. shape control).

2.1.4 Applications

In an actuating application, the converse piezoelectric effect is utilized as the actuators deform in response to a control signal or applied voltage.

As previously mentioned, piezoelectric polymers are rarely utilized as actuating mechanisms. Reference [2] employed polyvinylidene fluoride (PVDF), a polymer, in both a sensing and actuating role for vibration control of flexible beam elements.

Ceramics are more commonly used as actuators. Reference [16] provides a glimpse at the current activities of the strategic defense initiative office (SDIO) in this area, focusing on vibration control. In the area of rotorcraft, two distinctly different actuator configurations have been examined for higher harmonic control [3,4]. The first used directionally attached plates to torsionally activate blade sections and actuate a trailing edge flap. The magnitude of flapping vibrations was significantly reduced using active controls. The second utilized a push-pull configuration of bender elements.

Another actuating application, also detailed in Reference [4], is the active damping of truss members for large space structure applications. This study used commercially available actuators which utilize the d_{33} effect (the expansion direction coincides with the direction of polarization) to limit the vibration amplitude and settling time of transients induced by dynamic perturbations to the structure such as crew motion.

In the acoustics field, recent work [5] has focused on reducing cabin noise by applying active forces produced by bonded PZT actuators to the fuselage walls or frame. Finite impulse response (FIR) filters were utilized in a least means square minimization algorithm to control both an acoustic resonance and a structural resonance at two different frequencies. Reference [6] described the use of piezoelectric plates as independent actuators (bimorph configuration) on an aluminum beam in conjunction with an adaptive controller to attenuate flexural and extensional vibrations with frequencies up to 1100 Hz.

Reference [7] details experiments and analyses of a composite beam with distributed embedded actuators controlling structural modes from 11 to 150 Hz. Through feedback of velocity, structural damping increases of an order of magnitude were obtained. Results available from aeroelastic applications of piezoceramics are very limited. Static aeroelasticity has been the subject of investigations by Ehlers and Weisshaar [1,8,9]. They conducted analytical studies on laminated composite wings with embedded actuators, looking at pure torsional, and bending deformations. They reported that through feedback to embedded adaptive material layers, the divergence speed is altered, implying also that lift effectiveness is influenced. The augmentation or replacement of conventional aerodynamic control surfaces with strain actuation for aeroelastic control has been the focus of an analytical investigation of a typical section by Lazarus, Crawley and Lin [10]. They found that strain actuation via piezoelectric elements may provide a viable and effective alternative to articulated control surfaces for controlling aeroelastic response. Investigation of flutter suppression for lifting surfaces and panels has been done by Scott [11]. This analytical study considered controlling flutter at supersonic speeds using full state feedback. Reference [12] detailed the application of plates in a bimorph bender configuration to actively suppress flutter.

See Appendix C for an analysis of the expansion and contraction of the surface of an aircraft wing. A potential application of piezoelectric ceramics might be to attach ceramic wafers to the surfaces of a wing to cause the wing surface to expand or contract which will effect the control of the aircraft. Several experiments have used PZT wafers as actuation devices to statically reshape plate structures to increase aerodynamic forces such as lift. High-strain shape memory alloy (SMA) materials are being considered to effect larger static shape changes.

There has been much work done on vibration suppression and modal control with in truss structures using piezoelectric stacks, an example of which is given in reference [17].

Production applications of piezoelectric ceramics are found in the automobile industry. An example of their use is in controlling compliance in Toyota's electronic modulated suspension system. The system is a road stability and shock adjuster which detects bumps, dips, rough pavement and sudden lurches by the vehicle and then rapidly adjusts the shock absorbers to apply a softer or firmer damping force. The shock absorbers are continuously readjusted as the road conditions change so that rocking or wobbling is eliminated.[13]

2.1.5 Issues

Notable undesirable material characteristics are nonlinear response at high voltage levels, hysteresis and aging. These are more noticeable problems in piezoceramics. The properties of piezoelectric materials are nonlinear. A linearity assumption is valid for low applied voltages and small deformations. Nonlinearities of these materials have been well-documented by references [3,12,14]. Several nonlinear properties which have been found to have significance are the amplitude dependence of the field-strain relationship, creep, variations with mechanical strain, and depoling. These issues will not be addressed in detail here.

Yet another concern is that very high voltages may be required to deform thick actuating plates. This problem can be avoided by utilizing a multilayer configuration instead of increasingly thick single layer plates.

2.2 Magnetostriction Materials

2.2.1 Benefits and Drawbacks

Ferromagnetic materials allow for the creation of an elastic strain when subjected to an external magnetic field. This effect is called magnetostriction. Terfenol-D is the most commonly-known magnetostrictive material. It is capable of inducing strains up to .2%. Metglas is another magnetostrictive material. The maximum strain is significantly below what Terfenol-D produces, but has an advantage in that it can be manufactured as a foil for easy embedding in composites.

Advantages of magnetostrictors over piezoelectric ceramics have been detailed in Appendix D. They include reliability, stable material properties, easier manufacturing and flexibility.

2.2.2 Configurations and Applications

Terfenol-D has been proposed by Grumman as a means of activating a control surface to optimize the lift performance of an aircraft wing under varying flight conditions. The wing changes shape. Ribs and spars are replaced with active members containing rods of Terfenol-D. In order to maximize the displacement obtainable, a diamond-shape structure was constructed which can deflect the trailing edge by 60°. Terfenol-D has superior strength, higher modulus and wider operational bandwidth than shape memory alloys. It can generate enough force to overcome the aerodynamic loads and has low magnetic field requirements. Magnetostriction materials are currently under evaluation for shape change of torpedo control surfaces, gimballing cockpit simulators, and vibration damping of optical benches.

An integrated actuation system for individual control of helicopter main rotor blades using Terfenol-D actuators was proposed and evaluated in a small business innovative research (SBIR) investigation for the U.S. Army Aviation Laboratory, Fort Eustis, Virginia (see Appendix D). The purpose of adding the flaps was to provide higher harmonic control of the individual blades to cancel rotor-induced vibration, long a major concern for helicopters. The goal of the program is to reduce vibration by 90% which would represent a major improvement in helicopter technology.

2.3 Shape Memory Alloys

2.3.1 Benefits and Drawbacks

The ability of a material to recover its shape when activated by an external stimulus is termed the shape memory effect. Nitinol is the most common shape memory metal. Heat is the activating stimulus for this material. This material undergoes a change in crystal structure known as a reversible austenite to martensite phase transformation at a specific transformation temperature, dependent upon alloy composition. Young's modulus increases by almost a factor of 3. Shape memory alloys are capable of directly transforming heat into mechanical work. The heat can be produced by fluids, gases, or electricity. If the heating and cooling is controlled by pulsed direct electric current, repeated cyclic motions with high degrees of accuracy can be achieved.

An electrostrictive ceramic (PMN) has also been found to exhibit shape memory effects, but with an electric field being the stimulus.

There are several major concerns which need be addressed before SMAs can be used as actuators. They exhibit large amounts of hysteresis and have a very low bandwidth during the cooling half-cycle. The cooling problem has been investigated by Watson, [19]. The speed of an actuator is limited by the cooling rate. Water cooling is much faster but the power increase necessary is in most cases prohibitive; though water cooling provides a 10 times increase in bandwidth, the power is increased by approximately 20 times.

The nickel-titanium family of SMAs exhibits good force output and high resistivity along with comparatively low hysteresis in copper-modified alloys.

2.3.2 Configurations and Applications

Shape memory alloy reinforced composites use shape memory alloys as fiber reinforcements which can be stiffened or controlled by the addition of heat. Prior to embedding the shape memory alloy fibers within the resin, they are plastically elongated and constrained from contracting to their memorized length. A possible configuration of the SMA reinforced composite material is where the shape memory alloy fibers are embedded in the resin at a distance from the neutral axis. When the fibers are heated, they try to contract to their normal length and thus generate a uniformly distributed shear load along their entire length. This off-axis shear load causes the structure to bend. Transient and steady state vibration control can be accomplished with these composites as well as active buckling control and shape control.[20]

There are many fields which are currently investigating using shape memory alloys for a variety of applications. Shape memory alloys have been used since 1970 as the joining device in the hydraulic control lines of the F-14 Grumman Navy fighter. Goodyear Aerospace Corporation has been developing Nitinol for spacecraft antennae. A wire hemisphere of the material is crumpled into a tight ball less than 5 cm across. When heated above 77°C, the ball opens into its original shape, a fully formed antenna.[13] A system has also been proposed for active vibration damping and shape control on adaptive space structures.

2.4 Electrorheological Fluids

2.4.1 Benefits and Drawbacks

Electrorheological (ER) fluids exhibit coupling between their fluid dynamic and electrical behavior. When exposed to an electrical field, their viscosity, damping capability and shear strength increase. ER fluids are typically suspensions of fine particles in a liquid medium; the viscosity of the suspension can be changed dramatically by applying an electrical field. The electric field causes alignment of the particles in fiber like branches in the direction of the applied field. [13] ER fluids are suspensions consisting of hydrophilic (polarizable high-dielectric-constant) particles in a hydrophobic (dielectric) liquid.[1] In the absence of an electric field, ER fluids exhibit Newtonian flow characteristics; their strain rate is directly proportional to applied stress. However, when a sufficient electric field is applied, a yield stress phenomenon occurs such that no flow takes place until the stress exceeds a yield value which rises with increasing electric field strength. Because electrorheological fluids change their characteristics very rapidly when electric fields are applied or removed, they possess great potential for providing rapid response interface in controlled mechanical devices.[15]

2.4.2 Configurations and Applications

Typically, ER fluids have been utilized in mechanical systems such as electromechanical clutches, fluid-filled engine mounts, high speed valves and active dampers. Typical examples demonstrate the use of an electro-viscous or magneto-viscous fluid within a damper mount. The fluid is provided between opposing walls of a cavity in the mount member. The mount member is coupled between load elements to control the motion condition between them.

Control of the overall dynamic properties of structures is not easily or efficiently accomplished by localized damping, and in many cases cannot be accomplished to the extent desired by localized damping. Even for a simple plate-like structure of finite size there are an infinite number of frequencies at which resonance can occur. For each resonance, there is a different arrangement of nodal lines and points of maximum vibration over the surface of the plate.

Electronic actuator devices are placed at locations within the structure which produce amplified, tuned vibrations which responsively cancel the input motion vibration.

Damping of helicopter rotor blade vibrations by embedding ER fluids has been evaluated. The proposed system consists of a composite helicopter rotor containing pockets of ER fluid with top and bottom electrodes.

An active engine mount system has been proposed utilizing ER fluids. A system senses the dominant vibration frequency band and adjusts the viscosity and thus the stiffness of the fluid. Thus, the natural frequency of the system has been modified. This same concept can be applied for manned space structures, automobile engines, and robots.

2.5 Electrostriction Materials

2.5.1 Benefits and Drawbacks

Electrostrictive materials change dimensionally when an electric field is applied or generate voltage when loaded, like piezoelectric ceramics do. However, the induced strain of an electrostrictor is proportional to the square of the electric field, which creates unidirectional displacement regardless of polarity. Strains comparable to PZTs can be obtained with electrostrictive ceramics similar to PMN, and without the troubling hysteretic behavior shown by PZTs under high voltage fields. The nonlinear relation between strain and electric field in electrostrictive transducers can be used to tune the piezoelectric coefficient and the dielectric constant. [13]

2.5.2 Configurations and Applications

The most noted application of electrostrictive ceramics is the micron-level manipulation of deformable mirror-surface contours to create or correct optical effects. This is utilized for focusing space communication system optical mirrors and lasers.

Electrostrictive transducers have been used in a number of applications including adaptive optic system, scanning tunneling microscopes, and precision micropositioners. [13]

2.6 References

1. Ehlers, S.M., Aeroelastic Behavior of an Adaptive Lifting Surface, Ph.d Dissertation, Purdue University, 1991.

2. Miller, S. E. and Hubbard, J., Smart Components for Structural Vibration Control, *American Control Conference*, 1988, Atlanta, GA.

3. Spangler, R.L., Piezoelectric Actuators for Helicopter Rotor Control, M.S. Thesis, Massachusetts Institute of Technology, February, 1989.

4. Barrett, R., Intelligent Rotor Blade and Structures Development Using Directionally Attached Piezoelectric Crystals, M.S. Thesis University of Maryland Department of Aerospace Engineering, 1990.

5. Lefebvre, S., Active Control of Interior Noise Using Piezoelectric Actuators in a Large Scale Composite Fuselage Model, M.S. Thesis, Virginia Polytechnic Institute & State University, June 1991.

6. Silcox, R.J., Lefebvre, S., Metcalf, V.L., Beyer, T. and Fuller, C.R.; "Evaluation of Piezoceramic Actuators for Control of Aircraft Interior Noise," AIAA paper no. 92-02-091, Proceedings of the 14th AIAA Aeroacoustics Conference, Aachen, Germany, May, 1992

7. Fuller, C.R., Gibbs, G.P. and Silcox, R.J., "Simultaneous Active Control of Flexural and Extensional Waves in Beams,"J. of Intelligent Material Systems and Structures, vol. 1, no. 2, pp 235-247, April 1990.

8. Weisshaar, T.A., and Ehlers, S.M., Adaptive Static and Dynamic Aeroelastic Design, Proceedings of the 1991 International Forum on Aeroelasticity and Structural Dynamics, *Workshop on Smart Material Systems and Structures*, Aachen Deutschland, June 1991.

9. Ehlers, S.M., and Weisshaar, T.A., Static Aeroelastic Behavior of an Adaptive Laminated Piezoelectric Composite Wing, *Proceedings of the AIAA/ASME/ASCE/AHS/ASC 31st Structure, Structural Dynamics, and Materials Conference*, Part III pp 2340-2350, Long Beach, CA, April 1990.

10. Lazarus, K.B., Crawley, E.F., and Lin, C.Y., Fundamental Mechanisms of Aeroelastic Control with Control Surface and Strain Actuation, *Proceedings of the AIAA/ASME/ASCE/AHS/ASC 32nd Structure, Structural Dynamics, and Materials Conference*, Part III pp 1817-1831, Baltimore MD, April 1991.

11. Scott, R.C., Control of Flutter Using Adaptive Materials, M.S. Thesis, Purdue University, May 1990.

12. Heeg, J., An Analytical and Experimental Study to Investigate Flutter Suppression via Piezoelectric Actuation, M.S. Thesis, George Washington University, August 1991.

13. Newnham, R. E., and Ruschau, G, R., Smart Electroceramics, *Journal of the American Ceramic Society*, Vol 74, No. 3, March 1991.

14. Anderson, E.H., and Crawley, E.F., Piezoceramic Actuation of One- and Two-Dimensional Structures, Space Systems Laboratory, Massachusetts Institute of Technology, Cambridge, MA.

15. Carlson et. al. U.S. Patent No. 4,923,057 May 8, 1990.

16. Obal, M., Sater, J.M., Adaptive Structures Programs for the Strategic Defense Initiative Organization, 33rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, April 1992.

17. Umland, J.W. and Chen, G-S., Active Member Vibration Control for a 4 Meter Primary Reflector Support Structure, 33rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, April 1992.

18. Chaudhry, Z. and Rogers, C.A., Enhanced Structural Control with Discretely Attached Actuators, 33rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, April 1992.

19. Watson, R.E., Comparison of the Response of Shape Memory Alloy Actuators Using Air-Cooling, M.S. Thesis, Naval Postgraduate School, Dec. 1984.

20. Rogers, C.A., Liang, C. and Burke, D.K., Dynamic Control Concept Using Shape Memory Alloy Reinforced Plates, "Smart Materials, Structures and Mathematical Issues", Sept. 1988.

3 Sensory Materials

3.1 Fiber Optic Sensors

3.1.1 Introduction

The concept of smart structures involves the incorporation of sensors into a structural material to serve as a nervous system for health monitoring of the final product.[42] The sensors are implanted in the material at the time of processing and remain intact and available for interrogation during use.

The most common sensors being investigated for implanting in materials are fiber optic. Fiber optic sensors have been developed that can measure many physical and chemical properties and in many cases are more sensitive than alternative techniques. Considering many of the unique characteristics optical fibers possess, such as low mass, immunity to electromagnetic interference, compatibility with advanced fiber reinforced composites and the potential of a single optical fiber performing a multiple role (e.g., communication and a multiple sensor function), it is not surprising to see the emphasis on these sensors. Hence, the major portion of this section will be devoted to a review of research on fiber optic sensors for smart structures applications with a brief description of other types of sensors that may also be useful.

If we intend to monitor the health of a structure, we must consider which parameters should be measured to assure structural integrity. Carrying the analogy of a nervous system for structures a step further, we might say we want to sense "pain". That's the signal that warns an organism that something is wrong. However, what constitutes "pain" in an inanimate material? In fact we are a long way from anything resembling that sort of indicator in a structure. The question has rather been posed as, "What can we measure in a structure and would it be useful as an indicator of structural integrity?"

Ultimately, smart materials and structures will contain sensor elements that can monitor in-situ chemical and physical properties, including: state of cure, temperature, strain and vibration, acoustic emission, impact damage assessment, corrosion and aging. Aerospace applications of this emerging technology will be discussed and issues related to further advancement and timely deployment of smart structures will be considered.

3.1.2 Cure Monitoring

The curing cycle, consisting of precision programmed temperature and pressure regimes, is a critical step in the processing of fiber reinforced composite materials. The mechanical properties of the final product depend on the degree of cure. Fabrication of large parts is especially troublesome because the degree of cure may vary from point to point due to variable geometry. Variations in the starting material from batch to batch and differences in handling during prepreg layup result in different degrees of cure for identical curing conditions. Enhanced quality assurance can be achieved with the use of sensors for in-situ cure monitoring. During the lifetime of the structure these in-situ sensors can also serve the purpose of monitoring the integrity of the structure. For example an optical fiber implanted in the composite for cure monitoring can be the same fiber that is interrogated later to measure strain, temperature, acoustic emission, and other parameters that are potential indicators of structural health.

Several methods have been investigated for monitoring the cure state of a composite. The most notable of these is the system developed by Druy, which measures the FTIR spectrum of the resin during cure with an optical fiber.[16] The change in the infrared spectrum indicates the degree of conversion of the resin to the cured polymer. The system has been demonstrated for epoxy and polyimide materials with fluoride, chalcogenide and sapphire fibers.[17,18] Since the method monitors chemical changes during cure it will be useful for production as well as for optimizing curing programs for new resins.

Other techniques involve monitoring physical properties related to the state of cure. Afromowitz [1] has shown that an epoxy fiber which has been fully cured can serve as an indicator of degree of cure when embedded in a graphite/epoxy composite. Since the refractive index of the cured polymer is greater than that of the uncured resin, the embedded fiber behaves as an optical waveguide until the composite is fully cured. When the fully cured state is reached, the refractive indices are identical and the fiber no longer transmits light.

Fluorescence spectra of curing composites have been measured with in-situ optical fibers to indicate cure state.[26] The sensor can later be used as a monitor for composite aging and water absorption.[27]

Acoustic waveguides embedded in curing composites have been used to measure propagation properties of ultrasonic signals. Sun and Winfree have shown that the acoustic amplitude in a copper wire embedded in a curing epoxy is related to the temperature and cure state.[40] Similar acoustic behavior has been observed for polyester-fiberglass waveguides embedded in thermosetting materials.[22]

Dielectric devices have also been investigated for cure monitoring taking advantage of the change of dielectric loss as the resin cures.[24,37]

3.1.3 Structural monitoring

The ultimate performance, safety and reliability of future aircraft and spacecraft will depend upon the capability of the crew or an automated control system to respond to adverse situations that may jeopardize the mission. Smart structural components may provide the data required for an appropriate response. Embedded or attached optical fiber sensors allow the measurement of distributed strain and vibrational modes for the entire structure and would indicate deviations from the norm by comparison with a historical data base. In addition, the fiber optic sensors can provide feedback for control of structural vibrations.

Strain and vibration measurements have been demonstrated in several laboratories using different fiber interrogation methods. These include modal domain interference,[3,8,35] optical time domain reflectometry,[10] optical polarization changes,[4,29] optical interferometry,[5,9,19,30] frequency domain reflectometry [39] and an optical phase locked loop.[25]

Optical time domain methods were first used to determine external loading in composites by Claus and co-workers [10] and improved time and frequency domain methods have subsequently been used by several investigators.[36,39,44] A method has been developed which uses in line optical fiber splices as time domain markers for optical time domain reflectometry (OTDR). An optical source generates a train of fast risetime optical pulses which propagate in the fiber. Partially reflecting splices, inserted at intervals along the length of the fiber, produce a series of regularly spaced signals and if the fiber is strained the spacing between the signals changes indicating the strain on the fiber between splices.[44] The strain resolution of this OTDR based system is limited by the rise times of the optical input pulses and the detection electronics. Currently available systems, for example, allow discrimination of locations spaced as close as 0.1mm.

Distributed structural vibration measurements may be achieved using a modal domain sensing method. The technique is based on the principle that different modes in a waveguide having slightly different propagation times produce interference patterns. If a waveguide that supports two or three modes is attached to or embedded in a structure, it can sense bends in the structure through the interference conditions between the modes. Claus et. al. have demonstrated that such methods may be used to evaluate structural vibrations of beams.[7] Specifically the mode shape amplitudes of such vibrations may be determined by appropriate processing of the time domain modal interference signals.[35]

Rogowski et.al. have investigated the use of a modulated laser diode system to measure phase modulation in an optical fiber. The system is an optical phase locked loop.[31] A voltage controlled oscillator is used to directly modulate a GaAlAs laser and to provide a reference signal to a double balanced mixer. The laser radiation passes through a multimode optical fiber, is detected, amplified, and mixed with the reference signal to generate an error voltage. The phases of the two signals are maintained at quadrature by feedback of the DC error voltage from the mixer to the oscillator. A filter removes the radio frequency component coming from the mixer. With this configuration, any change in the phase of the modulation is compensated by a change in the modulation frequency. A change in phase length, ΔL, of the optical fiber will produce a change in frequency, ΔF, according to:

$$\Delta L/L = -\Delta F/F$$

where L is the effective path length (optical plus electronic) and F is the nominal frequency value.

The optical phase locked loop has been applied to the measurement of dynamic strain in a cantilever beam [32] and quasi-static and dynamic strain with an optical fiber implanted in a filament wound graphite/epoxy tube.[33] Rowe, et. al. have used similar radio frequency modulation techniques to monitor strain in composite materials.[34]

3.1.4 Non-Destructive Evaluation and Damage Detection

Embedded optical fibers allow not only cure monitoring and in-service lifetime measurements but may also be used to non-destructively evaluate material degradation and damage as the material ages. The modal domain sensing system described above has been applied specifically to the detection of acoustic emission in loaded composite specimens.[2] An optical fiber used as an acoustic transducer has a very wide bandwidth compared to conventional transducers. The electronic processing of such signals using conventional acoustic emission analysis procedures is complicated because the impulse response function of the fiber exhibits a much stronger low frequency response than piezoelectric ultrasonic transducers.[7]

Some level of damage detection may also be afforded using embedded optical fiber sensor methods which locate excessive internal strain by the breakage of optical fibers arranged in a two dimensional array.[13,23,28,43] The disadvantage of such techniques is that levels of damage that do not break fibers cannot be detected and once fibers are broken no additional data may be gathered.

The capability of this type of damage detection system has been extended to additionally allow the quantitative determination of two dimensional strain in materials using several methods. First, the two dimensional strain field may be determined using single mode optical fibers embedded in a grid array, with interferometric techniques used to measure strain along the individual fiber lengths, and numerical methods used on the multiple output signals to construct the strain field. This method has been applied to the measurement of quasi-static loads and impact induced residual stresses in simply supported graphite/epoxy composite panels.[11] Alternatively, optical intensity modulation caused by microbending can be used as the sensing mechanism.[36] Loading in a composite specimen causes changes in the microbend characteristics of embedded fibers and thus in the transmitted optical intensity. Similar numerical methods would be required to map two dimensional strain fields from multiple linear measurements obtained using this method.[14,15]

Fiber optic sensor technology can be combined with advanced material and structural concepts to produce a new class of materials with internal sensors for health monitoring - providing the opportunity for smart structures. There are many potential uses of such materials in aircraft and spacecraft, especially where critical structural components have been identified and using the new materials proves cost effective. Space Station will require some type of sensing system to monitor the vibrations of the structure and feedback information to control mechanisms. A fiber optic sensor system for monitoring strain seems ideally suited for this application since the structure is large and flexible and requires a method for dynamic control. At least some parts of future aircraft will have fiber optic sensors for monitoring strain and impact damage. Commercial aircraft may be able to extend their useful life through proper monitoring of load spectra directly from the fiber optic sensor. In addition, the cost of maintenance may be reduced through "maintenance for cause" based on actual environmental history rather than air time. Certainly, military aircraft would benefit from having a damage detection and evaluation capability during engagements. The information would be invaluable to the pilot for deciding on a course of action after suffering damage to the aircraft.

To realize these benefits some important issues must be addressed. Very little has been done to determine the effect of embedding fibers on the strength of the material. Czarnek has reported very different strain fields around an optical fiber depending on the orientation of the fiber with respect to adjoining plies in the graphite/epoxy composite.[6] The effect of fiber coatings on the response of the embedded fiber to various environmental parameters must be investigated. Their is some evidence that polyimide coated fibers are more suitable for strain measurements than standard acrylate coatings.[25] Also strain fields induced in the optical fiber from forces surrounding it when embedded or attached must be understood.[38]

Most of the early work has been done with standard communication fibers, but custom fibers with numerical apertures unsuitable for high speed communications may be more appropriate for sensing applications.[12]

Investigation of radiative properties of specialty optical fibers, as they relate to mechanical stress, may be of benefit for local strain measurements along an embedded fiber. Specially coated fibers may be useful for monitoring corrosion and aging in materials. Atomic oxygen is very corrosive to composite materials in near-earth orbit. Research is underway in our laboratory to measure the effects of atomic oxygen on composites and to monitor atomic oxygen with a fiber optic sensor.

Other exciting uses of this technology may be in monitoring strain in large structures such as buildings, ships, storage tanks, pressure vessels, dams and bridges.[20,41] The optical fibers with their low attenuation can literally span a bridge for miles and return information regarding structural integrity. The fibers may also find application to geodynamic monitoring as a low cost, large area sensors for strain/vibration associated with earthquake prediction. Fiber sensors have already been applied to monitoring oil pipelines for long distances and represent an emerging and enabling sensor technology.

Future advances in opto-electronics and signal processing will very likely open new avenues for sensing and make this technology an important part of NDE for assuring the safety and reliability of aircraft and spacecraft.

3.1.5 References

1. Afromowitz, M.A. and Lam, K. Y., "Fiber Optic Cure Sensor For Thermoset Composites," *Review of Progress in Quantitave Nondestructive Evaluation*, Vol. 8, edited by D. O. Thompson and D. E. Chimenti, Plenum Press, New York, 1989, p. 1467 .

2. Bennett, K. D., Claus, R. O. and Pindera, M. J., "Internal Monitoring of Acoustic Emission in Graphite-Epoxy Composites Using Imbedded Optical Fiber Sensors," *Review of Progress in Quantitave Nondestructive Evaluation*, Vol . 6, edited by D. O. Thompson and D. E. Chimenti, Plenum Press, New York, 1987, p. 331.

3. Bennett, K. D., McKeeman, J. C. and May, R. G. "Full-field analysis of modal domain sensor signals for structural control," *Proceedings SPIE*, Vol. 986, 1988, p. 85.

4. Brennan, B. W., "Dynamic Polarimetric Strain Gauge Characterization Study, " *Proceedings SPIE*, Vol . 986, 1988, p. 77.

5. Butter, C. D . and Hocker, G. B., "Fiber Optic Strain Gauge, " *Applied Optics*, Vol. 17, 1978, p. 2867.

6. Charnek, R., Guo, Y. F., Bennett, K. D. and Claus, R. O., "Interferometric Measurements of Strain Concentrations Induced By an Optical Fiber Embedded in a Fiber Reinforced Composite," *Proceedings SPIE*, Vol. 986, 1988, p. 43.

7. Claus, R. O. and Bennett, K. D. "Smart structures program at Virginia Tech, " *Proceedings SPIE*, Vol . 986, 1988, p. 12.

8. Claus, R. O. and Bennett, K. D., "Optical fiber modal domain detection of stress waves," *Proc. 1986 IEEE Ultrasonics Symp.* (Williamsburg, Va).

9. Claus, R. O. and Cantrell, J. H., Jr., "Detection of Ultrasonic Waves - Interferometer," *IEEE Ultrasonics Symposium*, 1980, p. 719.

10. Claus, R. O., Jackson, B. S. and Bennett, K. D., "Nondestructive Evaluation of Composite Materials by OTDR in Embedded Optical Fibers," *Proceedings SPIE*, Vol. 566, 1985.

11. Claus, R. O. and Wade, J. C., "Distributed Strain Measurement in a Rectangular Plate Using An Array of Optical Fiber Sensors," *Journal of Nondestructive Evaluation,* Vol. 4, 1985, p. 23.

12. Cozens, J. R., Green, M. and Yi, G., "Special Fibers for Sensing, " *Proceedings SPIE,* Vol.1011, 1988, p. 62.

13. Crane, R., Macander, A. B. and Gagorik, J., "Fiber Optics for a Damage Assessment System for Fiber Reinforced Plastic Composite Structures," *Review of Progress in Quantitave Nondestructive Evaluation,* Vol. 2, edited by D. O. Thompson and D. E. Chimenti, Plenum Press, New York, 1983, p. 1419.

14. Culshaw, B., "Optical Fibres in NDT: A Brief Review of Applications, " *NDT International,* Vol . 18, 1985, p. 265.

15. DePaula, R. P. and Udd, E., Editors, "Fiber-Optic and Laser Sensors IV, "*Proceedings SPIE,* Vol. 718, The International Society for Optical Engineering, Bellingham, Washington, 1987.

16. Druy, M. A., Elandjian, L. and Stevenson, W. A., "Composite Cure Monitoring With Infrared Transmitting Fibers, " *Proceedings SPIE,* Vol. 986, 1988, p. 130.

17. Druy, M. A. and Elandjian, L., "In-Situ (Autoclave) Cure Monitoring of Composites With IR Transmitting Optical Fibers," *Review of Progress in Quantitave Nondestructive Evaluation,* Vol. 9, edited by D. O. Thompson and D. E. Chimenti, Plenum Press, New York, 1990, in press.

18. Druy, M. A., Young, P. R., Stevenson, W. A. and Compton, D. A., "In-Situ Composite Cure Monitoring Using Infrared Transmitting Optical Fibers, " *SAMPE Journal,* Vol . 25, 1989, p. 11.

19. Dunphy, J. R., Meltz, G. and Elkow, R. M., "Distributed Strain Sensing with a Twin-core Fiber Optic Sensor," *Instrument Society of America Transactions,* Vol. 26, 1987, p. 7.

20. Friedlander, G. D ., "Smart Structures, " *Mechanical Engineering,* Vol. 110, 1988, p. 78.

21. Griffiths, W. R. and Lamson, R. C., "Adoption of an Electro-Optic Monitoring System to Aerospace Structures, " *Proceedings SPIE,* Vol. 838, 1987 .

22. Harrold R. T . and San jana, Z . N., "Nondestructive Evaluation of the Curing of Resin Prepreg Using an Acoustic Waveguide Sensor," *Review of Progress in Quantitave Nondestructive Evaluation,* Vol. 6, edited by D. 0. Thompson and D. E. Chimenti, Plenum Press, New York, 1987, p. 1277 .

23. Hofer, B., "Fibre Optic Damage Detection in Composite Structures ", *Composites,* September, 1987, p. 309.

24. Kranbuehl, D., Delos, S., Hoff, M., Haverty, P., Hoffman, R., Godfrey, J. and Freeman, W.,"Frequency Dependent Impedance Analysis: Monitoring the Chemistry and Rheology During Cure", *Proceedings of the Society of Plastics Engineers,* Vol. 45, 1987, p. 1031.

25. Leka, L. G. and Bayo, E., " A Close Look at the Embedment of Optical Fibers into Composite Structures," *Journal of Composites Technology and Research,* Vol. 11, 1989, p. 106.

26. Levy, R. L., "A New Fiber-Optic Sensor for Monitoring the Composite-Cure Process", *Polymeric Materials Science and Engineering,* Vol. 54, 1986, p.321.

27. Levy, R. L. and Schwab, S. D., "Performance Characteristics of the Fluorescence Optrode Cure Sensor (FOCS)", *Polymeric Materials Science and Engineering,* Vol. 56, 1987, p. 169.

28. Measures, R. M., Glossop, N. D. W., Lymer, J., Leblanc, M., West, J., Dubois, S., Tsaw, W. and Tennyson, R. C., "Structurally integrated fiber optic damage assessment system for composite materials," *Proceedings SPIE,* Vol. 986, p. 120.

29. Mermelstein, M. D., "All Fiber Polarimetric Sensor . " *Applied Optics,* Vol. 25, 1986, p. 1256.

30. Reddy, M., Bennett, K. D. and Claus, R. O., "Embedded optical fiber sensor of differential strain in composites," *Review of Progress in Quantitave Nondestructive Evaluation,* Vol. 6, edited by D. O. Thompson and D. E. Chimenti, Plenum Press, New York, 1987, p. 1241.

31. Rogowski, R. S., Heyman, J. S., Holben, M. S., Jr., and Sullivan, P., "A method for monitoring strain in large structures: Optical and radio frequency devices", *Review of Progress in Quantitave Nondestructive Evaluation,* Vol. 6, edited by D. O. Thompson and D. E. Chimenti, Plenum Press, New York, 1987, p. 559.

32. Rogowski, R. S., Heyman, J. S., Holben, M. S., Jr., Dehart, D. W. and Doederlein, T., "Sensor Technology for Smart Structures," *Proceedings of the 35th International Instrumentation Symposium,* 1989, p. 177.

33. Rogowski, R. S., Heyman, J. S., Holben, M. S., Jr., and Dehart, D. W., "Fiber Optic Strain Measurements in Filament Wound Graphite-Epoxy Tubes Containing Embedded Fibers, " *Proceedings SPIE,* Vol. 986, 1988, p. 194 .

34. Rowe, W. J., Rausch, E. O. and Dean, P. D., "Embedded Optical Fiber Strain Sensor For Composite Structure Applications," *Proceedings SPIE,* Vol. 718, 1987, p. 266.

35. Safaai-Jazi, A. and Claus, R. O. "Synthesis of interference patterns in few-mode optical fibers, " *Proceedings SPIE,* Vol. 986, 1988, p. 180 .

36. Schoenwald, J. S. and Beckham, P. M., "Distributed fiber-optic sensor for passive and active stabilization of large structures," *Review of Progress in Quantitave Nondestructive Evaluation,* Vol. 7, edited by D. O. Thompson and D. E. Chimenti, Plenum Press, New York, 1988, p. 565.

37. Senturia, S. D. et. al., "In-situ Measurement of the Properties of Curing Systems with Microdielectrometry", *Journal of Adhesion,* Vol. 15, 1982, p.69.

38. Sirkis, J. S. and Haslach, H. W., Jr., "Strain Component Separation in Surface-Mounted Interferometric Optical Fiber Strain Sensors," *Proceedings SPIE,* Vol. 1170, 1989, in press.

39. Spillman, W. B. Jr., Fuhr, P. L. and Anderson, B. L. "Performance of integrated source/detector combinations for smart skins incoherent optical frequency domain reflectometry (IOFDR) distributed fiber optic sensors," *Proceedings SPIE,* Vol. 986, 1988, p. 106.

40. Sun, K. J. and Winfree, W. P., "Propagation of Acoustic Waves in a Copper Wire Embedded in a Curing Epoxy," *Proceedings of the IEEE Ultrasonics Symposium,* 1987, p. 439.

41. Takahashi, K., "Sensor Materials for the Future: Intelligent Materials," *Sensors and Actuators,* Vol. 13, 1988, p. 3.

42. Udd, Eric, Fiber Optic Smart Structures and Skins, *Proceedings SPIE*, Vol. 986, The International Society for Optical Engineering, Bellingham, Washington, 1988.

43. Waite, S. R. and Sage, G. N., "The Failure of Optical Fibres Embedded in Composite Materials," *Composites,* Vol. 19, 1988, p. 288.

44. Zimmermann, B. D., Murphy, K. A. and Claus, R. O. "Local strain measurements using optical fiber splices and time domain reflectometry," *Review of Progress in Quantitave Nondestructive Evaluation,* Vol. 7, edited by D. O. Thompson and D. E. Chimenti, Plenum Press, New York, 1988, p. 553.

3.2 Dielectric Loss Sensors

3.2.1 Definition

Dielectric loss sensors function as the name implies; they measure the change in the electric field for a specified material or specimen. The sensor works similar to a parallel capacitor in that it senses loss or change in current or properties. Dielectric measurements are performed by placing a sample of the material to be studied between two conducting electrodes, applying a time-varying voltage between the electrodes, and measuring the resulting time-varying current. For further explanation of dielectric measuring techniques, see Reference [1].

3.2.2 Historical Perspective

Measurements of dielectric properties have been used to monitor chemical reactions in organic materials for more than fifty years. In 1934, Kienle and Race [2] reported the use of dielectric measurements to study polyesterification reactions. Many of the major issues were identified in that early paper, such as the fact that ionic conductivity often dominates the observed dielectric properties, the correlation between viscosity and conductivity early in the curing process, and the possible contribution of orientable dipoles and sample heterogeneities to measured dielectric properties.

Many other papers were written since 1934 documenting these types of techniques to measure chemical change. The description of some of these findings as it relates to the curing of thermosets can be found in Reference [1].

3.2.3 Property Change

In recent years, dielectric measurements have been utilized to study the curing of thermosets. Efforts have been made to develop a method to simultaneously measure the viscosity and dielectric properties during various cure schedules to understand the relationships [3]. A commercially available, interdigitated comb electrode dielectric sensor [4,5] was used for the dielectric measurements for the studies of Reference [3]. The Micromet Eumetric System II microdielectrometer was embedded in the material and was capable of operation in a frequency range of 0.005 to 10,000 Hz.

Reference [3] explains the usefulness of measuring the dielectric loss factor during the curing process as it relates to ionic concentration and mobility. The ion mobility is a direct function of the polymer segment mobility which change dramatically as the resin cures. Therefore by monitoring the dielectric loss, the cure process can be tracked.

Additional information on dielectric loss sensors related to thermosets can be found in Reference [1].

3.2.4 Weight and Torque

Some years ago, Gast reported on an electromagnetic balance which was combined with an electrostatic attachment for measuring torque [6]. Conceivable applications of an instrument would include measurement of density and viscosity, determination of permittivity and dielectric loss, and other combinations of properties that are functions of temperature, pressure, and other variables.

Additional work has been performed by using a magnetic suspension balance system to measure weight and torque [7]. This can be accomplished simply by using a pair of mutually attracting horseshoe magnets where the poles are kept at a predetermined distance by automatic control. The lower magnet carries two vanes of copper sheet, aligned in a horizontal plane, which are in the sensitivity range of symmetrically arranged inductive sensors fixed to the upper magnets. The sensors are connected in a Wheatstone bridge in such a manner that the distance and angular position of the vanes under load can be measured simultaneously giving weight and torque. For more details and further explanation, see Reference [7].

3.2.5 Electromagnetic Radiation and Heat Transfer

A technique for measuring dielectric loss tangents has been developed in connection with measuring various parameters of pyroelectric materials. These materials have the potential as detectors of electromagnetic radiation and sensors in heat transfer measurements. This technique uses well-known concepts and requires only conventional laboratory equipment. The technique allows for measuring dielectric loss tangents in the range of 0.1 to 2 with frequencies from 15 Hz to the megahertz range. Additional information is found in Reference [8].

3.2.6 References

1. Senturia, S.D. and Sheppard, N.F., Jr: "Dielectric Analysis of Thermoset Cure," *Advances in Polymer Science,* Vol. 80, 1, (1986).

2. Kienle, R.H. and Race, H.H.: "The Electrical, Chemical and Physical Properties of Alkyd Resins," *Trans. Electrochem. Soc.,* 65,87,(1934).

3. Gotro, Jeffery and Yandrasits, Michael: "Simultaneous Dielectric and Dynamic Mechanical Analysis of Thermosetting Polymers," *Polymer Engineering and Science,* Vol. 29, No. 5, (March 1989).

4. Senturia, S. and Garverick, S.: US Patent No. 4,423,371.

5. Senturia, S., Sheppard, N., Lee, H., and Day, D.: (*J. Phys. D*), 1, 117, (1968).

6. Gast, Th.: Thermal Analysis, Vol. 1, *Proceedings Third Icta Davos* (1971), p. 235-241.

7. Gast, Th. and Koppe, K.: "Simultaneous Measurement of Weight and Torque in Controlled Atmospheres By Magnetic Suspension, "*Journal of Vacuum Science Technology*, 15(2), (March/April 1978).

8. Burdick, G.A. and Hickman, T.G.: "Technique For Measuring Dielectric Loss Tangent," *The Review of Scientific Instruments*, Vol. 37, No. 8 (August 1966).

3.3 Piezoelectric Sensors

3.3.1 Overview

Considerable research has been conducted by aerospace and commercial industries in the development of piezoelectric (PE) materials as sensors for a wide range of applications. Defense applications include submarine hull hydrophones for detecting sonar and active noise suppression [1], acoustic-signature health monitoring for aging aircraft, in-flight deicing and aeroelastic tailoring, vibration suppression for helicopter blades [2], detonators and shock wave gages, to name a few. Some of the many commercial uses of PE sensors/actuator systems are shown in Appendix E.

Some of NASA's future space missions will require challenging material and design developments. Structures composed of antennas, reflectors, optical benches, telescopes, optical interferometers and truss members will require high dimensional control, on the order of nanometers (in some cases picometers) over very large distances, up to a 100 meters [3]. These will require precision pointing, shape control and rapid retargeting. Once initial alignment is attained, precision will have to be maintained in the face of on-board disturbances and temperature variations. For truss structure, the active strut member must be able to carry normal loads while also able to sense and damp out disturbances through actuation. Since deflection levels may not exceed a few micrometers at a maximum, strain sensing/actuation is considered the most effective approach. Candidate materials include piezoelectrics, electrostrictors, and magnetostrictors. More details of PE uses as sensors follows.

3.3.2 PE Materials/Applications

3.3.2.1 PE Film

PE films may be fabricated from ceramic or polymeric material. PE ceramic films are being developed for memory devices and data storage, which requires deposition in thin film form for application in silicon circuits. PE ceramic films/plates are also being studied as actuators in structural composites.

Polymeric PE films are the most recently discovered PE material and the most widely used as sensing devises [4]. They convert a mechanical force to an electrical response and, conversely, an electrical signal to a mechanical motion. They are more pliant, flexible, tough and lightweight than previously known piezoelectric materials. The most widely used PE film is based on polyvinylidene difluoride (PVDF), which has the highest PE and pyroelectric activities of any known polymer (Appendix E). High PE response is associated with the polar form of the polymer in which the hydrogen and fluorine atoms are arranged to give the maximum dipole moment per unit molecular cell. This arrangement is produced by means of treating the material in an intense electric field . The resulting product exhibits a large net polarization which gives the film its high PE activity. The level of PE activity is defined by the piezoelectric strain and stress constants, d_{31} and g_{31} respectively. By definition, the first subscript refers to the axis of polarization and the second to the axis of induced stress or strain. Typical properties of PE film (PVDF) are listed in Appendix F. A discussion of some applications follows.

In aircraft concepts designers have been studying ways to change the shape and stiffness of wings according to flight conditions. The current Air Force "smart skins" program deals with the incorporation of sensors and actuators within composite aircraft panel structures. Researchers at MIT spatially distributed PVDF film, bounded to a steel beam structure, such that the output was selectively proportional to a particular deformation pattern [5]. In this manner, the PE film served as "modal sensors" capable of supplying information on individual dynamic mode shapes. This direct measurement of the natural modes of vibration could help eliminate control system estimation techniques based on complex algorithms that decompose a vibration into these natural modes. These techniques are often limited in accuracy and dynamic response.

Innovative Dynamics, Ithaca, NY has proposed an in-flight aircraft deicing system using PE film to sense changes in wing-vibration signature that result from ice build-up. If the system detects ice, it triggers an eddy-current actuator to "ping" the wing, knocking the ice loose. The flexible PE film remained intact, whereas the ridged PE ceramics were subject to breakage when the wing was pinged. Innovative Dynamics is also applying PE films for acoustic-signature mapping of aging aircraft structures. Eddy-current actuators are used to "ping" the structure, while the flexible PE film monitors vibrations, sending an electric signal proportional to the pressure of the vibration. Changes in the acoustic-signature map are used to detect rivet-line corrosion, fatigue cracks, loosening engine mounts and attachments. At Westinghouse Electric Corp., PE ceramics are placed on waveguides and embedded into composite structures representative of submarine hulls. Acoustic signals generated by cracking or delamination of the composite are transmitted by the wave guides to the PE ceramics which convert the impulses to electric signals allowing location of the fault. PE film is suggested for vibration-damping systems in air-conditioning ducts, fuselage noise-and vibration control, and sound damping of large truck bodies.

3.3.2.2 PE Composites

PE composites may generally be described as multiple-phase systems in which the overall PE properties that result from the composition can not be obtained from any known single-phase material. A PE composite may be designed to have unique properties that are best suited to a specific application. These properties include the dielectric constant, PE coefficients (d_{ij}), voltage coefficients (g_{ij}), PE coupling factors (k_{ij}), density and degree of brittleness, among others. Monolithic PE ceramics, although having excellent electromechanical coupling qualities, are too brittle for hydrophone use and have too high an acoustic impedance for ultrasonic imaging devices. However selected properties from these ceramics may be derived by incorporating them into a composite design. This typically involves a PE ceramic in the form of a rod, fiber or powder embedded in a resin matrix. The ceramic provides the electromechanical coupling required while the matrix compliance may be tailored to the application through proper resin selection. Some of the developments in this area are discussed as follows.

3.3.2.3 Hydrophones

A considerable amount of work has been done through The Office of Naval Research (ONR) and Penn State University toward the development of piezocomposites for hydrophones [6]. A hydrophone is an underwater transducer used to detect sound. The "figure of merit" for hydrophone performance is the product of the hydrostatic piezoelectric coefficient, d_h, times the hydrostatic voltage coefficient, g_h. Other desirable properties for a hydrophone are low density for better acoustical matching with water, little or no variation of the hydrostatic piezoelectric coefficient and the hydrostatic voltage coefficient with pressure, temperature or frequency, and high compliance and flexibility so the transducer can withstand mechanical shock and conform to any surface. A recent study of calcium doped $PbTiO3$ (PT) rods in two types of epoxy polymers showed that the hydrostatic piezoelectric coefficient of the composites increased with increasing ceramic volume fraction (see Appendix G and reference 8). For 20% PT rod loading, the hydrostatic voltage coefficient values at room temperature were 67 mV-m/N with the stiffer epoxy and 50 mV-m/N with the more compliant epoxy. These values compare to 30 mV-m/N for the monolithic ceramic PT and 2 to 3 mV-m/N for monolithic PZT. The hydroacoustic response of the composite was found to be frequency independent from 100 Hz to 6 kHz. These results suggest that piezoelectric composites represent a class of promising new materials for underwater acoustic applications.

Another form of piezocomposites, being considered for sonar detection is being developed using PE fibers. CPS Superconductor, Milford Ma. has developed a process to fabricate PE fiber. Commercially available PZT 5H powder is compounded with a proprietary polymer system and extruded at an elevated temperature (melt spun "green fiber"). The polymer is removed by heating and the ceramic powder is sintered into highly dense ceramic filaments and rods. Any sinterable ceramic or metal powder can be used in this process to produce a variety of monofilament shapes and sizes. Fiber can be spun into various diameters (3 to 50 mil) and cross-sectional shapes, such as hollow tubes, square and rectangular, and others. These fibers are used to make d_{33} piezocomposites. After the epoxy casting and cure the PE composite is sliced, ground and polished. Air-dried silver is applied to the composites flat surface followed by poling in an oil bath at 1.6 KV/MM, 120°C for 15 min. Piezoelectic measurements of this system were conducted at the Materials Research Laboratory, Pennsylvania State University, and are shown in Appendix H. The effect of varying fiber/resin type, volume fraction, and fiber diameter size (among other factors) on the resulting PE properties is an exciting area of research.

3.3.2.4 Ultrasonic Imaging

A PE fiber/epoxy composite has been developed for medical ultrasonic imaging applications [9]. The PZT fiber volume is greater than 65%. This gives the material a high electromechanical coupling coefficient (k_t) for needed high sensitivity. The low compliance polymer allows a relatively low acoustic impedance to match that of tissue for medical imaging. The requirements for this application can not be met by monolitic PZT (high coupling coefficient/ high acoustic impedance) or PE polymers (low acoustic-impedance/low coupling coefficient) alone.

3.3.2.5 Vibration and Shape Control

Smart strut technology for application to spacecraft vibration using embedded PE sensors and actuators in graphite/epoxy structures (d_{13} actuation) is being studied at MIT, TRW, and Boeing, among others. At MIT, a composite panel with embedded actuation was constructed and tested. The graphite/epoxy plate contains 32 PE actuators and localized PE sensors and accelerometers, incorporated into the structure by making small cutouts in individual graphite/epoxy plies during layup. Test results indicate that the PE ceramics and connecting wires caused only 20% tensile strength reduction in composite beams that could be excited or damped with these inserted materials. MIT has also developed FEA models to strategically locate PE actuators/sensors in high-strain regions of the structure. Their models also aid in the selection of ceramic modulus, most compatible with the structure.

TRW has embedded thin PZT actuator and sensor wafers in graphite/epoxy, polycyanate, and thermoplastic members. These have then been subjected to fatigue and thermal cycling. It was found that fatigue loading, at less than 1500 microstrain, actually enhanced the actuator/sensor feedforward by 1-10% (see Appendix I). This is most likely due to the degraded stiffness of the laminate being pushed upon. Beyond 1500 microstrain, a deterioration of 12% feedforward resulted. Greater deterioration to feedforward resulted from thermal cycling (10-30%), indicating the design need to lower the coefficient of thermal expansion mismatch of materials.

For the U.S. Army, Georgia Tech researchers have been working on ways to improve helicopter blades. PE film sensors and shape memory alloy have been bonded to beam models of the blades. By inducing appropriate twisting effects, smart helicopter blades can vibrate less and be quieter.

Boeing has also embedded PE ceramic sensor/actuators in an aluminum beam and has demonstrated active damping. Their research topics include developing attachment adhesive at the piezoelectric interface which will improve feedforward response, reducing piezoelectric fatigue and microcracking, coating thin piezoelectric material on graphite fibers, and integrating piezoelectric materials with electronics.

3.3.3 References

1. W.A. Smith, "The Role of Piezocomposites in Ultrasonic Transducers," *Proc. IEEE Ultrasonics Symp.*, pp. 755-766 (1990).

2. S. Hanagud, M.W. Obal, and A.J. Calise, "Optimal Vibration Control by the Use of Piezoceramic Sensors and Actuators," *28th AIAA SDM Dynamics Specialists Conf. Proc.*, AIAA paper 87-987 (1987).

3. Anderson, Moore, Fanson, "Development of an Active Truss Element for Control of Precision Structures," *Optical Engr.*, vol. 29 No 11, 1333, (1990).

4. Kynar Piezo Film Technical Manual, *Atochem Sensors*, Inc. Valley Forge, Pa. (1991).

5. E. Crawley and K. Lazarus, "Induced Strain Actuation of Isotropic and Anisotropic Plates," in *30th AIAA SDM Conf. Proc.*, AIAA paper 89-1326 (1989).

6. W.A. Smith, A.A. Shaulov and B.A. Auld, "Design of Piezocomposites for Ultrasonic Transducers," *Ferroelectrics*, 91, 155-162 (1989).

7. R.Y. Ting, A.A. Shaulov and W.A. Smith, " PE Properties of 1-3 Composites of a Calcium Modified Lead Titinate in Epoxy Resins," *Proc. IEEE Ultrasonics Symp.*, pp. 707-710 (1990).

8. "Green Fiber Fabrication Method for PE Composites;" ONR contract # N00014-91-C-0036 to Ceramics Process Systems, Milford, Mass. (1991).

9. H. Takeuchi, H. Masuzawa, C. Nakaya and Y. Ito, " Medical Ultrasonic Probe Using Electrostrictive-Ceramics/Polymer Composite," *Proc. IEEE Ultrasonics Symp.*, pp. 705-708 (1989).

10. J. de Luis and E. Crawley, " Experimental Results of Active Control on a Prototype Intelligent Structure," in *31st AIAA SDM Dynamics Spec. Conf. Proc.* AIAA paper 90-1163 (1990).

11. R.E. Newnham, Q.C. Xu, S. Kumar, "Smart Ceramics," *Ferroelectrics*, 102, 259-266, (1990).

12. R.Y. Ting, " The Hydroacoustic Behavior of Piezoelectric Materials," *Ferroelectrics* 102, 215-224 (1990).

13. Collins, Padilla, H. von Flowtow, "Design, Manufacture, and Application to Space Robotics of Distributed Piezoelectric Film Sensors," *31st Structures, Structural Dynamics and Materials Conference*, AIAA paper, (1990).

14. H. Takeuchi, H. Masuzawa, C. Nakaya and Y. Ito, "Relaxor Ferroelectric Transducers," *Proc. IEEE Ultrasonics Symp.*, pp. 697-705 (1990).

15. R.C. Buchanan, "Ceramic Materials for Electronics," 2nd edition, Marcel Dekker, Inc. (1991).

16. A. Preumont, J. Dufour, and C. Malekian, "Active Damping by a Local Force Feedback with Piezoelectric Actuators," *AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 32nd*, Baltimore, MD, Apr. 8-10, (1991).

17. T. W. Lim, "Sensor Placement for On-Orbit Modal Testing," *AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 32nd*, Baltimore, MD, Apr.8-10, 1991.

18. R.E. Newnham, G.R. Ruschau, "Smart Electroceramics," *J. Am. Ceram. Soc.*, 74 (3), 463-480, (1991).

19. R.E. Newnham, Q.C. Xu, S. Kumar and L.E. Cross, "Smart Ceramics," *J. Wave-Material Interaction*, 4,3-10, (1989).

20. J. Fanson, G. Blackwood, and C. Chu, "Active Member Control of Precision Structures," in *30th AIAA SDM Conf. Proc.*, AIAA paper 89, 1329, (1989).

21. T. Bailey and J.E. Hubbard, "Distributed Piezoelectric-Polymer Active Vibration Control of a Cantilever Beam," *J. Guidance Control and Dynamics*, 8 (5), 605-611, (1985).

22. E.H. Anderson, D.M. Moore, and J.L. Fanson, "Development of an Active Member Using Piezoelectric and Electrostrictive Actuation for Control of Precision Structures," *AIAA SDM Conf.*, Part 4, April 2-4, (1990).

23. S. Im and S.N. Atluri, "Effects of a Piezo-Actuator on a Finitely Deformed Beam Subjected to General Loading," *AIAA J.*, 27 (12), 1800-1807, (1989).

24. B.K. Wada, J.L. Fanson and E.F. Crawley, "Adaptive Structures," *Mechanical Engineering*, Vol. 112, No. 11, pp. 41-46, Nov. (1990).

25. D.W. Miller, S.A. Collins, and S.P. Peltzman, "Development of Spacially Convolving Sensors for Structural Applications," *Proc. of the 31st AIAA/ASME/ASCE/AHS Structures, Structural Dynamics and Materials Conf.*, Long Beach, Ca., April 2-4, Paper No. AIAA-90-0949, (1990).

26. Fanson, Anderson, Rapp, "Active Structures for use in Precision Control of Large Optical Systems," *Optical Engr.*, vol. 29 No. 11, 1320, (1990).

27. C.K. Lee, "Laminated Piezopolymer Plates for Torsion and Bending Sensors and Actuators," *J. Acoustical Society of America*, Vol. 85, No. 6, pp. 2432-2439, (1989).

28. Piezo Systems Product Catalog, Piezo Systems, Inc., Cambridge, Ma., (1990).

3.4 Applications of Embedded Sensors in Aircraft

3.4.1 Introduction

One of the promising applications of new techniques and materials involved in the field of smart structures is the provision of embedded sensors in the structure. Because of the small dimensions of these devices and ability to install them during construction of the airplane, the sensors could conceivably be much more numerous and widely distributed than the presently used discrete sensors. Such devices are currently in the research stage, and are not available for service use. This discussion is intended to show possible desirable applications of these techniques.

The applications of embedded sensors considered herein are as follows:

Certification tests
In-flight structural monitoring
Load history recording
Sensing of feedback quantities for control
Aeronautical and structural research

Much of the discussion is based on earlier experience in flight research on instrumented airplanes. Because of the need for more extensive instrumentation in these tests than in service use, some of the applications have been explored, or at least studied in a preliminary way. The availability of distributed sensors, together with the data-handling capability of present-day computers, would allow routine use of techniques that have previously been considered only in research projects.

3.4.2 Certification Tests

Each new airplane is required to go through certification tests to verify that it meets its requirements for strength, performance, maneuverability, and handling qualities. These tests are hazardous because the limits of the flight envelope are being explored while the airplane is still new and untried. Present methods to minimize danger consist in gradually increasing the limits of the flight envelope, while examining the data on motions and loads with specially installed instrumentation. The instrumentation is expensive and may be rather minimal in its coverage because the difficulty of fitting additional equipment in an already crowded airframe. It is quite possible that a critical problem may be missed because of inadequate measurements.

The rationale of the certification tests is that the load distribution, stability, and stalling characteristics have been predicted by theory and by wind-tunnel testing. As a result, at a given load factor the distribution of structural loads can be predicted. Measurements at a few points can be considered to validate the adequacy of the entire structure. In practice, however, the load distribution in flight may be different from that predicted. Structural failures may therefore occur at localized regions where the loads have been predicted incorrectly. In general, there is no method to measure the detailed load distribution during certification tests.

Further problems may occur during dynamic maneuvers because of aeroelastic distortions or structural oscillations. Such problems may be noted by the test instrumentation, but the detailed analysis of the problem to determine a cure requires knowledge of mode shapes that cannot be measured by the limited test instrumentation.

The availability of distributed sensors with on-line analysis of the data would greatly enhance the safety of testing, while eliminating the expense of special test instrumentation. In general, even if not all the sensors could be hooked up at once, detailed studies of localized trouble spots could be made, and mode shapes of the entire structure could be measured to enable checks of dynamic stability predicted from previous analysis and simulation studies.

3.4.3 In-Flight Structural Monitoring

When an airplane is placed in service following completion of the certification tests, the assumption is made that airplanes build to the same design will be free from structural failure. In most cases, the loads encountered in service are less than the values successfully demonstrated, so that the airplane does not often encounter catastrophic failure in flight. More subtle forms of failure due to fatigue and corrosion are, however, a source of concern. The method of checking for fatigue cracks is to inspect the airplane at periodic intervals, using magnetic or x-ray techniques, to locate incipient cracks before they become serious. Many parts of an airplane structure are difficult to inspect, however, and a crack may go unnoticed until it causes failure of member. Corrosion is even more insidious, because it can attack a large number of rivets or other members simultaneously without visible effects. Some method to monitor such deterioration on a continuous basis would be very desirable.

In airplanes with composite structures, the possibility exists to install distributed sensors in the form of optical fibers or other devices in sufficient numbers to give a detailed coverage of the structure. Such sensors could have multiple uses, but one simple application would be to detect cracks that break the sensors in a localized region. In this way, cracks could be detected on a continuing basis and repairs could be made before the condition became serious.

3.4.4 Load History Recording

Recording the history of loads experienced by an airplane in flight is a traditional method to obtain data applicable to the design of new airplanes. Instruments such as VG and VGH recorders have been distributed by NACA and NASA to the airplanes and military services to obtain data in service operations. Usually, only a few airplanes in a fleet can be so outfitted. In more recent times, flight recorders are carried by all commercial airplanes. These instrumented record on a continuous tape so that only the last half hour of flight is available on the record. Usually these records are examined only in case of an accident.

Continuous recording of data from distributed sensors would allow a much more detailed study of service loads. These data would be of particular interest for study of fatigue, because the many smaller loads as well as the few large loads would be recorded. Also, many parts of the structure susceptible to fatigue loads, but not usually investigated in service airplanes, could be studied. These members could include hinge brackets, wing ribs, control rods, etc. With the availability of such data, future airplanes could be designed with less excess weight now required to provide for the margin of error in knowledge of the loads.

3.4.5 Sensing of Feedback Quantities for Control

Control of the rigid-body motions of an airplane is usually accomplished by using a set of instruments located in the cockpit area. These instruments, measuring quantities such as airplane attitude, accelerations, angular velocities, etc. form the nerve center of the airplane and are used to provide feedback signals for the control system as well as to provide cockpit displays for the pilot. Many quantities required in modern airplane control systems, however, can not be measured at a central location and require remote sensors connected by wiring, or, in the case of digital systems, a data bus, to the central computer. For example, angle of attack is measured using a sensor either in the nose or on the wing, sideslip is measured by vanes under the fuselage, control positions are measured with pickups on the control surfaces, etc. These remote sensors and their associated wiring form a major source of unreliability. All of this equipment is provided in triplicate or quadruplicate, with voting to rule out failed components, in order to provide the high reliability required in a control system.

Although the redundancy provided in an modern airplane required a great deal of design effort and installation difficulty, the degree of redundancy is negligible compared to that in the nervous systems of living creatures. Feedback sensors are provided for every hair and muscle fiber. The destruction of large numbers of these sensors, though it gives warning of a problem in the form of pain, may not interfere with normal activities. Such a picture forms a goal for the use of embedded sensors in airplanes. Modern techniques using distributed sensors give the possibility to emulate the capabilities of living creatures, as well as possibly to reduce the installation problems of providing a control system separate from the primary structure.

A field of research that has received considerable emphasis is the design of active systems to damp structural oscillations or to suppress flutter. Before such systems can be considered, however, it is necessary to have instrumentation to measure in flight the oscillation mode shapes and stresses throughout the structure. As soon as large, flexible airplanes became available, the NACA undertook studies to investigate the techniques required to obtain such data. A series of tests were conducted on an instrumented B-47 airplane, starting in 1952, to measure wing motions and stresses in dynamic maneuvers involving structural oscillations. The airplane was instrumented by installing strain gages on the front and rear spars at four stations on the span, in addition to an optical instrument to measure structural displacements at these stations and at various locations on the fuselage and tail. The standard research instrumentation to measure airplane rigid-body motions was also installed. The installation of equipment was very difficult because of the lack of accessibility to many parts of the structure. Installing the wiring and strain gages in the wing required over a year's work at Langley, after which flight tests were conducted at the High-speed Flight Research Center (now the Dryden Flight Research Facility) at Edwards, California.

A number of reports were published on the techniques of strain-gage instrumentation and on the B-47 tests. The method of calibration of strain gages is presented in ref. [1]. Presumably, similar techniques could be used in the case of distributed instrumentation. Some results of the flight tests on the B-47 are given in references [2-4].

An important application of measurements of dynamic oscillations of an airplane structure is the prevention of flutter at speeds beyond the flutter speed of the uncontrolled vehicle. Such a system might be desirable because it could result in lower structural weight or give the designer more freedom in choosing a configuration. A research study of this possibility was made by the Air Force in the LAMS project, an acronym for "load alleviation and mode stabilization". A B-52 was fitted with instrumentation and servomechanisms to operate the controls to suppress flutter. A flutter mode could be destabilized by means of a weight on the wing, resulting in flutter within the normal flight envelope. The automatic system was used to stabilize the flutter mode. In case of failure of the automatic system, the weight could be dropped to restore stability. The results of this project are given in references [5].

While the LAMS project was intended to demonstrate the feasibility of in-flight flutter suppression, it was limited in its capabilities by the state of the art of servomechanism design, since it depended on analog systems. More complex instrumentation and on-board calculation is required to make such a system feasible. As yet, no service airplanes have appeared with automatic flutter suppression systems. Among the problems of a practical installation is the separation of structural oscillations due to rough air from those due to flutter. It is possible that the greater capabilities provided by embedded sensors would make such a system feasible.

3.4.6 Aeronautical and Structural Research

The difficulty of instrumenting an airplane for research purposes has already been pointed out. If the distributed instrumentation were incorporated in the materials used in the structure, the airplane could be equipped for many types of studies not contemplated at the time of the original design. Even wind-tunnel models could benefit from these techniques. A study in reference [6] describes an optical system for measuring the static deflections of a wing in the tunnel. Obtaining and evaluating the data by this method is a long and tedious process. Embedded instrumentation would allow computer analyses of the data, and might give sufficient coverage to obtain these results.

The measurement of pressure distribution is very important subject in aeronautical research. As yet, pressure sensors have not been developed that can be incorporated in the materials used in the structure. If such sensors were developed, many capabilities would be presented of value both for research and service operations. Pressure capsules attached to embedded conductors might also simplify installations, but the capsules would have to be very thin and smooth to avoid disturbing a laminar boundary layer. The use of embedded devices for pressure measurements is a desirable subject for future research.

3.4.7 References

1. Skopinski, T. H., Aiken, William S. Jr., and Houston, Wilber B.: Calibration of Strain-Gage Installations in Aircraft Structures for the Measurement of Flight Loads. NACA TN 2993, Aug., 1953.

2. Donegan, James J., and Huss, Carl R.: Study of Some Effects of Structural Flexibility on the Longitudinal Motions and Loads as Obtained from Flight Measurements of a Swept-Wing Bomber. NACA RM L54L16, May 20, 1955.

3. Rhyne, Richard H.: Measurements of the Motions of a Large Swept-Wing Airplane in Rough Air. NACA TN 4310, Sept., 1958.

4. Rhyne, Richard H., and Murrow, Harold W.: Effects of Airplane Flexibility on Wind Strains in Rough Air at 500 Feet as Determined by Flight Tests of a Large Swept-Wing Airplane. NACA TN 4107, Sept., 1957.

5. Burris, P. M. and Bender, M. A.: - Aircraft Load Alleviation and Mode Stabilization (LAMS). AFFDL-TR-68-158, April , 1969.

6. Byrdsong, Thomas A., Adams, Richard R., and Sandford, Maynard C.: close Range Photogrammetric Measurement of Static Deflections of an Aeroelastic Supercritical Wing. NASA TM 4194, Dec., 1990.

3.5 Smart/Intelligent Sensors

A smart/intelligent sensor or an intelligent system of sensors/instruments is a critical element of a smart/intelligent structure. Definition of the words "Smart Sensor" has been evolving and expected to change its evolutionary processes with time. A smart sensor [1,2,3,4] may be considered as one that is capable of: (1) converting some form of environmental stimulus into an electrical signal; (2) providing signal conditioning; (3) executing commands and logical functions; (4) communicating through a bi-directional digital bus; (5) making solid decisions based on incomplete information gathered from multiple sensor inputs using fuzzy logic; and (6) performing such functions as health monitoring and auto-calibration.

Technology for the first five capabilities are already available, namely very large scale integration (VLSI) and micromachining/microtechnology. Some commercial sensors with such capabilities are already on the market, such sensors are CMOS based monolithic capacitive pressure sensors with signal conditioning circuit and micromachined silicon accelerometer with digital circuitry on the same chip. These sensors are inherently small and well suited for embedding as an integral part of a smart structure.

A new type of an acoustic transducer array [5] has been developed using polyvinylidene difluoride (PVF2) as a sensing material which is placed on a metal-oxide-semiconductor field-effect transistor (MOSFET). A linear 34-element receiving transducer array has been built and evaluated. A radio frequency (RF) telemetry system for powering and control of smart sensor has been reported [6]. The sensor is a single channel implantable microstimulator for neuromuscular stimulator with a 12 volt rechargeable battery which is periodically charged using a

RF telemetry system. In addition to these smart features, an inclusion of sleep/wake mode for the smart structure would be desirable for saving on-board power source.

As many sensors and actuators are distributed over a structure, a bilateral communication bus for the sensors and actuators and processors becomes an important part of the smart structure. An architecture and interface for a process controller has been investigated [7] for a number of fundamental issues in system partitioning, controller architecture, sensor function, and sensor testing/compensation. The sensor bus interface is addressable, programmable, self-testing, compatible with a bi-directional digital sensor bus, and offers 12-bit accuracy.

Integration of current technologies in VLSI, micromachining, and system architecture for a distributed sensor/actuator structure will result in a miniature/microscale smart sensor/actuator system that is most suitable for embedment of smart sensors and actuators into a smart structure. Many of these technologies are already available but they need to be integrated to realize a smart structure. Major areas of these technology areas are listed below.

1) Micromachining
2) Specialized mixed signal silicon device integrated circuit fabrication (application specific integrated circuit)(ASIC)
3) Architecture and interface system design and implementation
4) Embedment technology

The second technology area, ASIC, is the most costly area though the ASIC technology is readily available, a technology that integrate micromachining and VLSI circuits is a specialized area which is beginning to appear within semiconductor industry, due to an increased demand of accelerometers, pressure sensors, and flow meters from the automobile industry. As an alternative and less expensive approach, use of multiple chip module (MCM) hybrid circuits in place of ASIC devices will be the most reasonable alternative avenue to pursue before a total monolithic ASIC system is sought.

The above discussions center on the implementation of the sensor hardware. However, sensor information may be augmented by incorporating data processing, information extraction and decision making capability as part of the sensor design. These elements may dictate the design of the sensor element. In many ways then the structure may become the sensor element as the response of the structure is defined and compared to previous measurements or predictions. For applications such as condition monitoring, it is desirable to monitor large none instrumented sections of a structure quickly and on a regular basis. By using discrete sensor elements and mapping the response in time and space, the transfer of vibrational energy through a structure may be defined.

Several new techniques have evolved in recent years that combine signal analysis with discrete sensor information to yield information about none instrumented sections of a structure by correlating excitation and response measurements at discrete points. These measurements are functions of the loading distribution and the structural characteristics for those parts of the structure that carry energy between the measurement points. This approach in effect makes the structure the sensor by modeling and/or monitoring the multidimensional path of the structural response and comparing such to a previously defined response.

3.5.1 Time-Frequency Analysis

The work of Bolton and Wahl [8,9] makes use of a time-frequency analysis of structural impulse responses to reveal the wave types and paths carrying significant energy through a structure. Since each wave-type (i.e. flexural, torsional, extensional...) is characterized by its own dispersion relation, each wave-type may be associated with particular features appearing in the time-frequency domain representation of the impulse response. In this work the Wigner Distribution is used as a means for obtaining the time-frequency representations. Other methods use sonograms[10] and the Choi-Williams distribution[11].

By using a fixed excitation distribution, pattern recognition technology will allow feature extraction from this type of data that may be related to the structural parameters. In this way, changes in the characteristics of the structure between measurements made at different times may be determined. Using a distribution of sensors and/or actuators, changes in parameters may be isolated to decreasingly smaller sections of the structure for problem identification.

3.5.2 Prediction of Dynamic Loads using Neural Networks

Condition monitoring often is implemented by a recording of loading as a function of time. This however requires the use of an extensive array of sensors to provide the required information. A method of indirectly monitoring component loads through common flight variables is demonstrated which requires only an a priori model of the response/excitation relationship. This method will allow for both linear and non-linear responses.

An artificial neural network model learns these response/excitation relationships through exposure to a database of measured records on a test vehicle for a range of load histories. The ANN model, utilizing standard recorded flight variables as inputs, is trained to predict time-varying and oscillatory loads on critical components. Interpolative and extrapolative capabilities have been demonstrated[12] with agreement between predicted and measured loads on the order of 90% to 95%.

3.5.3 References

1. Najafi, K., "Smart Sensors," J. Micromechanics and Microtechnology, Vol. 1., pp 86-102, 1991

2. Brignell, J. E., "1989 Smart Sensors, A Comprehensive Survey," edited by W. Gopel, J. Hesse and J.N. Zemel, vol. 1, (New York, N.Y.)

3. Giachino, J.M., "1986 Smart Sensors," Sensors and Actuators, vol. 10, 239-248

4. Juds, S.M., "Toward a Definition of Smart Sensors," Sensors, pp 2-3, July, 1991

5. Swartz, R.G. and Plummer, J.D., "Integrated Silicon-PVF2 Acoustic Transducer Arrays," IEEE Trans. Electron Devices, vol. ED-26, No. 12, December 1979

6. Akin, T., Ziaie, B., and Najafi, K., "RF Telemetry and Control of Hermetically Sealed Integrated Sensors and Actuators," IEEE Solid-State Sensor and Actuator Workshop, Technical Digest, pp 145-9, Hilton-Head, SC, 1990

7. Najafi, N and Wise, K.D., "an Organization and Interface for Sensor-Driven Semiconductor Process Control Systems," IEEE Trans. Semiconductor Manufacturing, vol. 3, No. 4, November 1990

8. Wahl, T.J. and Bolton, J.S.; "Identification of Structureborne Noise Components by the Use of Time-Frequency Filtering," AIAA paper no. 90-3967, presented at 13th AIAA Aeroacoustic Conference, Tallahassee, FL, October 1990.

9. Wahl, T.J. "The prediction and analysis of transient structural responses," MSME Thesis, School of Mechanical Engineering, Purdue University, 1990.

10. Hodges, C.H., Power, J. and Woodhouse, J.; "The Use of the Sonogram in Structural Acoustics and an Application to the Vibration of Cylindrical Shells," J. of Sound and Vibration vol. 101, pp 203-218, 1985.

11. Choi, H.I. and Williams, W.J. "Improved time-frequency distributions: Theory and Applications," IEEE Trans. ASSP 37(6), pp 862-871, 1989.

12. Cook, A. B. et al; "The Prediction of Non-linear dynamic loads on helicopters from flight variables using artificial neural networks," AIAA 14th Aeroacoustic Conference, Aachen Germany, May 11-14,1992

4 Control of Smart/Intelligent Structures

4.1 Introduction

This chapter provides an overview of current techniques and concepts to implement control concepts on real systems. Many technologies and approaches are currently under study and it is not feasible to mention all of the current activities for control system implementation on smart/intelligent structures. It is intended to examine the current trends of this field and to highlight those expected to be important to future progress.

Generally, the intent of adding control to structural elements is to extend the functional capability of the primary structure in some way. This may include a change in structural strength, dynamic properties, or geometry which may provide noise, vibration or flutter control, dynamic margin, maneuverability enhancement or gust alleviation. These are by no means inclusive of the control purposes. Other mission criteria include condition monitoring and damage tolerance (survivability) and redundant system design. Not only is it possible to determine the extent of a failure or predict it, but structural elements may be included such that loads may be routed around a damaged subsection. An intelligent structure of this nature would require a new type of collocated sensor and actuator system including a processor for local control of the structure and mutual communication to the central processor which is the global controller.

Using present technology, these systems generally include discrete sensors, actuators and controllers. These are currently implemented as add-on transducers and external control systems. This approach requires an extensive maze of interconnecting wires to provide the necessary communication between these elements, provides little weight or structural utilization of the control elements and limits integration of the system. Ideally, it is desirable to integrate the transducer elements into the structure such that they contribute to the overall static and dynamic load capability or damping properties. Sensors and actuators may be the integral parts of load bearing members of the structure. Consequently, design of a given structure requires to be coordinated with that of sensors, structures, and local processors as well as communication media. An approach of discrete component design/construction may be no longer applicable in many cases. An integrated design/construction approach will be a logical one to pursue

There are many approaches to control law design for structural systems. These include the state-space approach, classical control design methods and neural networks. Although some of these methods do not require an explicit model of the system to be controlled, they cannot be applied as a black box with control inputs and outputs. All of the approaches are governed by the same laws of observability and controllability. These require that the motions to be controlled be observed by the sensor system without violating temporal or spatial sampling criteria. It also requires that the control system can couple effectively into these motions or modes in order to exercise control. For instance, a time domain processor can effectively provide a rate variable from the time history of the displacement. However, this approach cannot provide additional modal information or improved spatial resolution from a limited number of transducers.

It is not likely that any one method of control is the best suited control approach for any given situation as the strengths differ for each control strategy. However, one may envision an integrated approach blending best technologies into a distributed hierarchical control over concurrent processors with anthropomorphic intelligence.

The state space approach relies heavily upon an accurate modeling of the structural system and control elements to derive an analytical model. The performance and stability depends intricately upon the accuracy of this model and errors introduced due to measurements, environment, or an inadequate number of states being considered can have catastrophic results. However this approach integrates a more complete understanding of the control problem than all of the other approaches. Every aspect of the physical structure and the control system is modeled. The effect of all parameters of the system can be investigated as well as the excitation. The stability margins can be defined as well as any limits of the excitation bounds. This modeling criteria however is a major shortcoming of this approach however. It is generally very difficult to derive an accurate model for a complicated physical system. These systems work primarily at lower frequencies because the order of the numerical models generally used is tractable. For higher order modes, it is generally difficult to specify their resonant frequencies to the required degree of accuracy.

Systems that use a simple feedback of velocity or displacement can be made quite effective, even for multiple input/output (MIMO) systems. A feedback gain is defined between a sensing element and an actuator element that provides the required control. However, it is generally required that these systems have a negligible time delay of the system response in the frequency range for which control is to exercised. Often, for low frequencies, this is not an unreasonable restriction. However, for most cases that have been implemented, the sensor and actuator are collocated on the structure. For more complicated structures, higher frequencies, wider bandwidth or where it is not convenient to collocate the transducers, this approach is not viable.

Controllers based upon measured open loop transfer functions have been implemented. A measurement of the response to be controlled is measured by a sensing element. The transfer function measured between this sensing element and a controller excitation is known a' priori and is used to calculate the controller input required to exercise control over the response. Variations allow this approach to define the transfer function on-line using coherence methods. These systems can be quite useful for harmonic disturbances as an estimate of the disturbance can often be derived or sensed and the system loop closed. However, these systems are quite sensitive to changes in their environment and excitation spectra. In addition, these systems are often found to be unstable. One approach to this problem is to add some adaptability to the model and provide an on-line estimate of the system parameters using various system identification approaches.

Adaptive closed loop controllers have emerged in recent years that are based upon a real time least means squares (LMS) minimization algorithms. These systems are generally based upon linear digital filter models, in which the filter parameters (coefficients) are treated as the free variables of a minimization procedure. The object of the procedure is to minimize some error function related to the difference between the measured system response and the desired system response. This approach is extended and generalized to higher order and non-linear systems with the emergence of neural network based controllers. These systems however do not explicitly integrate any system model into the controller. The limits on the implementation due to traditional controllability and detectability issues must be derived separately and integrated from an intuitive viewpoint. Finally, general stability criteria are typically not addressed in this approach.

Artificial neural networks expand and generalize upon the above concept. Neural networks were part of the attempts towards artificial intelligence initially developed in the 1950's and 1960's. These early studies diverged through the 1960's into engineering approaches that implemented statistical pattern classification, control theory and adaptive filters; and symbolic manipulation representations of artificial intelligence and cognitive science. The engineering approaches will be stressed in this survey. This approach has provided algorithms for a broad range of practical problems. Neural networks are used to classify information (temporal and/or spatial) into ranges of classes for decision making (i.e. pattern recognition). Using the general ability of mapping from one large set of variables such as sensor systems to another such as control actions, they have demonstrated the capability to capture critical behavior for very complex functions. This capability extends to multi-variable non-linear processes and may include both feedforward and/or feedback systems. A wide range of approaches is evolving in this technology area and the areas of highest potential are not well delineated.

Finally, modeling of system components is critical to the performance of the control system and essential for the system simulation. Any experimental work on control of a complex smart/intelligent system is expected to be very costly and time consuming, an extensive system simulation before any attempt of experimental evaluation is preferred. Modeling of sensors and actuators are as important as those of basic system structure. Modeling areas includes: 1) finite element model and system identification 2) model identification using hardware 3) state space model for sensors and actuators 4) modeling of environmental and aging effects of components 5) modeling of nonlinear properties of sensors and actuators 6) modal analysis.

4.2 Modern Control Approaches

This section overviews control algorithm approaches that are model based. This means an analytical model is developed that integrates the plant dynamics into a controller that performs the desired control function. In a state space formulation, a numerical procedure is typically used to integrate through the governing equations to predict the desired controller output from known system states. For rate feedback methods, the model is used to derive controller gains (frequency response functions) that operate on input rate information. These gains are typically fixed but adaptive systems are now quite common that monitor the system characteristics and change the parameters in the model as needed. These techniques encompass many methods and variations and this section is not meant to be all inclusive but merely an indication of available technologies.

4.2.1 Model Based Feedback Control Approaches (State Space)

Jacques, et al. [1] presented control design of an experimental testbed with assumptions of collocated disturbance source and actuator and that of performance metric and sensor. Control design method includes measurement of transfer function from actuator to sensor, use of nonlinear curve fitting technique to obtain state space model of the system, reduction of model order, design of linear quadratic Gaussian (LQG) controller, and removal of dynamics from controller that do not contribute to stability and affect the performance slightly.

Allen, Lauffer, and Marek [2] present design implementation of structural control of a flexible truss structure with a multiple input-output control processor and piezoelectric sensors and actuators. Structural control performed with reduced LQG design technique required model accuracy which is much greater than the accuracy required for response analysis or structural design purposes. A NASTRAN finite element model was used as the basis for the control design model. The optimal projection controller showed good correlation between the analytical and experimental performances. System identification techniques proved to be invaluable for the finite element model improvement. Hardware implementation of structural control design and techniques is highly recommended as the analytical study results are highly prone to the modeling and analysis assumptions.

Murotsu, Senda, and Hisaji [3] present optimal configuration control of the adaptive truss structures. The optimal configuration has been formulated with minimizing performance index corresponding to the demanded task. However, it was stated that the computational burden is too excessive to be an effective real-time tool. Two alternative approaches were presented with the relaxed conditions of optimality, that is local optimal configuration and the specified asymptotic convergence of the work vector.

4.2.2 Active Vibration Control

Hyland, Collins, Phillips, and King [4] present the highlights of control design process and performance obtained from the ACES and Mini-MAST structures of NASA using both centralized and decentralized controllers. The paper also discusses about the design procedure and describes the substantial performance improvement achieved with a decentralized control for active vibration suppression of flexible structures. Hong, Varadan, and Varadan [5] performed a series of active vibration control of a thin plate. Coupled multi-mode optimal control procedures for the plate have been developed using Rayleigh-Ritz method to obtain the approximated mode shape constant. A proportional type damping has been implemented to obtain a closed-form solution of the differential eigenvalue problem for the damping system. Experimental verification of uni-disc type collocated sensors and actuators was made, and theoretical and experimental work on transducer sizes and positions has been presented.

Hanagud, Babu, Stalford, and Won [6] present an adaptive structure that can adopt to failures such as debonding of the sensor during its life and take into account unmodeled dynamics. The controller is designed with several assumptions such as reduced degrees of freedom, uncertainty bounds, extent of debonding, Euler-Bernoulli beam theory and flawless beam.

4.2.3 Stochastics

Jacques and Miller [7] present use of low order models to identify and study four mechanisms through which a structural change might influence the controlled performance. Interaction of the structures and the control has been discussed by formulating a cost function in terms of structural parameters and control gains. H-2 and H-infinity performance metrics are considered for a preliminary design of the control structures. Huang and Knowles [8] uses H-infinity optimization technique as the control design methodology for the control of a large space structure. It is also pointed out that a test of a large scale structure in 1-g conditions is difficult to be carried out for verification of the control design.

Athans, Agguiero, Bielecki, Boker, Douglas, Gilpin, and Lublin, [9] discuss novel robust LQR control strategy under assumption of full state feedback and uncertain energy interpretation. Extension to robust H-2/H-infinity approach with output feedback and dynamic compensation is considered with its application to MACE. Motivation of this effort is to design of robust multi-variable controllers, obtain a state-space model of system for design, and derive a minimal multi-variable model.

4.2.4 Adaptive Control

Trent and Pak [10] present their work on the development of the methodology to design and test controllers that will provide stable environments for payloads mounted on space platforms. Difficulties of obtaining accurate models of structural dynamics of large space structures are pointed out along with structural characteristics that may change during the spacecraft lifetime due to hardware failures and operational or environmentally induced changes. Adaptive control techniques with on-line system identification approach is presented with various concerns about controls-structures interaction (CSI) issues.

Sekine, Shibayama, Iwasawa, and Tagawa [11] describes the adaptive control system of flexible truss structures with a piezoelectric actuator as an active member. The active member actuator prove to be effective in controlling flexible truss structures statically and dynamically.

Melcher and Wimmel [12] describe modern controllers which are based on digital real-time filters, adaptation algorithms and high speed signal processor systems. It is intended to show the stringent controller requirements can be met with the use of modern adaptive signal processing containing sophisticated adaptive algorithm routines of an up-to-date software environment and high speed computational hardware system.

4.2.5 Integrated Controls-Structures Design

Maghami, Joshi, Price, Lim, Walz, Armstrong, and Gupta [13,14,15,16] proposed an approach of integrated design methodology of the structural and control system. This approach has been applied to the integrated design of a class of flexible spacecraft, a geostationary platform and a ground-based flexible structure. An optimization-based approach has been developed with a set of design variables consist of both control and structural design variables. The approach of static and dynamic dissipative control laws are used to provide robust stability in the presence of both parametric and nonparametric uncertainties. The substantially superior numerical results have been obtained with the integrated design approach compared to that of the conventional approach. It was noted that standard high performance model-based controllers such as H-2 or H-infinity are generally not robust to deal with parametric uncertainties of unmodeled dynamics and certain types of actuator and sensor nonlinearities. Iwatsubo, Kawamura, Adachi, and Ikeda [17] made an approach to the simultaneous optimum design of the structural and control system of a flexible structure. This paper describes that the gradients of the characteristic values and shape of the structure are taken as structural design variables, while the number of the structural design variables is constant, and the numerical example of this simultaneous optimum design is presented.

4.3 Adaptive Feedforward Control Systems

Control systems implementations based upon the pioneering work of Widrow [18,19] emerged from a digital signal processing approach. This work had its origins in the need to provide noise and echo rejection in long distance phone lines [20]. Because of its origins in digital signal processing, this work grew up as a separate entity from traditional or modern controls approaches which accounts for its conflicting definitions and conventions. The term adaptive here refers to ability of the controller to change its parameters in order to minimize a specified function. This it does without regard to any previous specified system model. It simply modifies the coefficients of an a' priori specified digital filter to attain this goal. This is in contrast to a modern controls approach to adaptive control discussed earlier.

The original physical system was all electronic and the disturbance to be rejected was broad band noise correlated with the desired signal but delayed in time. For all of these implementations, it is assumed that a signal (input) that is correlated with the disturbance is available for feeding forward in the controller. The frequency range over which control was to be exercised was the primary voice bandwidth, from about 500 Hz to 5000 Hz. Because of the high frequency range to be controlled, it was found that transients imposed by changes in the controller state decayed quickly. Therefore, the adaptive process of the controller is considered to be going from one steady state to another steady state. In formulating the LMS adaptive process, it is also assumed that an instantaneous estimate of error function may be substituted for the true value of the error function. Using this assumption, the algorithm was implemented such that at every sample update, the controller updates all of its parameters. Because this occurs at 10,000 times a second, the algorithm is found to converge in the mean. Thus, it often does not matter that the error estimate may have a great deal of uncertainty.

In the early to mid 1980's, this work was picked up by Burgess working in acoustical noise control [21] as a means to implement what is now commonly referred to as active noise control. From the early work of Lueg [22] and Olsen[23] using analog controllers, the use of destructive interference for noise control achieved limited success. Work in the 1970's and early 1980's utilized analog controllers and sensing arrays to implement control systems typically with analog controllers and early digital controllers. This work is reviewed by extensively by Ffowcs-Williams [24] and Warnaka [25]. The emergence of special purpose digital signal processing CPU's by Texas Instruments, AT&T and Motorola in the 1980's allowed this technology to progress rapidly as digital filters and adaptive algorithms could be implemented in real time on widely available, cheap systems.

The control algorithms that have been developed based upon Widrow's work [18] operate in the time domain. The optimization process updates the digital filter coefficients based upon an algorithm that samples the error function and reference signal continuously. This work has been extended to multiple input/output systems by Elliott et al [26]. This algorithm operates in the time domain such that the coefficients of an array of finite impulse response (FIR) filters, whose outputs are linearly coupled to another array of error detection points, are adapted so that the sum of all the mean square error signals is minimized. A special case of this adaptive controller is for control of a periodic, synchronously sampled response. The implementation of the above LMS algorithm for this case can be made very efficient as described in Reference [27]. Furthermore, its behavior can be represented exactly as that of a linear time-invariant comb filter.

The above work all applied finite impulse response filters as the central algorithm of the controller. Using this approach, it was much easier to insure stability of the control system. However, for controllers with a strong frequency dependence, i.e. resonant systems, this would typically require many filter coefficients (degrees of freedom) to provide the required control. Another approach to this problem was to use infinite impulse response (IIR) filters as the controller element. This allows a more complicated frequency response function to be approximated with significantly fewer coefficients (degrees of freedom). However, stability much more difficult to insure. These issues were discussed extensively by Johnson [28]. Current work by Eriksson [29] utilizes an IIR based control algorithm in a variation of Widrow's approach. This system is available commercially and has been working in industrial noise control applications for several years.

The first applications of this technology was control of low frequency plane wave noise propagation in ducts [30,31] to more recent work demonstrating control of random multi-modal modes in ducts [32]. The approach of the Roure [31] and Silcox [32] utilized an adaptive algorithm based in the frequency domain, although the controller was implemented in the time domain as a digital FIR filter.

More recent work by Bullmore, et. al. [33] and Silcox, et. al. [34] has investigated the control of interior noise in aircraft cabins. Typical noise problems in propeller and turbofan powered aircraft are harmonic in content and quite amenable to adaptive feedforward control. A tachometer signal from the turbomachinery provides the necessary reference signal and the limited harmonic content allows relatively simple controllers to be used. Two flight tests by Elliott, et. al. [35] and Ross, et. al. [36] on a British Aerospace 748 demonstrated significant noise reduction using distributions of acoustic sources. These flight tests utilized adaptive feedforward control and an open loop transfer function approach respectively. However, they required up to 32 control sources and 64 error sensors to provide this control. Similar result were obtained by Boeing Aircraft on a deHavilland Dash 8 aircraft in unpublished results.

Recent work has demonstrated a more efficient approach for controlling low to mid frequency structural sound radiation, termed active structural acoustic control (ASAC). In contrast to using acoustic control transducers, ASAC applies control forces directly to the structure such that some estimate of the radiated pressure field is minimized. The primary advantage of this approach is that effective control can be implemented with fewer control actuators. Other advantages are related to the physical implementation of the control in that the transducers can be arranged to be reasonably compact, or integrated as part of the structure.

Early work in ASAC was carried out at NASA Langley and VPI&SU [37] in 1985 where it was demonstrated that sound transmission into cylinders could be controlled by point forces applied to the cylinder wall. Again, the application was to develop advanced techniques for controlling interior noise in aircraft. It was shown that only certain structural modes couple or radiate to the interior space and it thus was necessary to control only these modes. This effect was termed modal suppression. As the structural motion that gives rise to the pressure response is being controlled, the interior sound field is reduced globally independent of its modal shape. This work was extended at Douglas Aircraft on a full scale DC-9 fuselage. Global control of structure-borne interior noise transmitted through the engine pylons using only two point force control actuators was demonstrated [38]. Weight, mounting considerations and control spillover effects has led to recent cooperative work at NASA and VPI&SU to study the use of piezoceramic actuators bonded to structural elements [39]. On a full scale composite fuselage model, a 4 actuator, 6 sensor system has achieved interior global attenuation of 8 to 15 dB over a range of test conditions for exterior airborne excitations [40]. Optimization of the transducer size and distribution is expected to significantly improve performance [41,42].

Another important application of ASAC is in controlling marine hull radiated sound and is being investigated under research funded by ONR/DARPA. Early work in this area studied control of free field radiation from lightly loaded panels [43]. It was demonstrated that sound radiated into a free-field could also be globally attenuated with a limited number of control actuators [44]. However, another mechanism of control was observed. For the off-resonant cases examined, a reduction in sound radiation occurred with little (or an increase) change in the averaged structural response. It was concluded that the residual or closed loop structural response has a lower radiation efficiency for the same level of response [43]. This effect was termed modal restructuring. More recently it was demonstrated that modal suppression corresponds to a decrease in all structural wave-number components while modal restructuring corresponds to a reduction only in the supersonic (radiating) components; the subsonic components are largely unaffected [45]. The significance of modal restructuring is that large attenuations of radiated sound can be achieved by an appropriate change in the controlled structural mode shapes without affecting the overall amplitude. This approach is shown to require significantly less control energy.

Other work on free field application of ASAC have centered on using optimally shaped piezoelectric sensors and actuators bonded or embedded in the structure [46] (an adaptive or smart structure). Emphasis has been placed on shaping the sensors so that the radiating components of the structural motions are observed, i.e. the sensor acts as a structural wave number filter. Good reductions in radiated sound levels for both on and off resonance conditions were observed. This work has now been extended to include the influence of heavy fluid loading on structural motions [47]. Experiments performed cooperatively between VPI&SU and NRL have shown that the ASAC technique still provides high global attenuations when the radiation loading induces significant modal coupling.

4.4 Artificial Neural Networks

Artificial neural networks encompass a broad class of concepts relating to classification, prediction, control and decision making. These systems as implemented in engineering environments are generalizations of adaptive controllers. The systems are generally implemented such that they "learn" about their control functions by example. This is generally accomplished though a process where the neural network is given a series of input and resulting outputs. The systems attempt to predict the supplied output (result) by operating on the input vector and adjusting the internal parameters of the neural network. In this way, it operates much like an adaptive digital filter except that it is not restricted to linear systems. The method which is used to train the system is a subject of much debate. The most common approach uses a back propagation algorithm which employs gradient information about the neural net model to adjust the weights of the model [48]. This technique is often cited as being slow to converge and requires a large data base to train. An extension to this technique is termed dynamic back propagation and is discussed by Narendra [49]. This approach attempts to optimize the structure of the neural network as well as the network parameters themselves. Hoskins and Vagners [50] discuss stability criteria for a closed loop system using neural controllers based on approximate models of the plant.

Barron [51] bases a general adaptive polynomial neural network upon mathematical approximation theory and statistical decision theory. In this approach, the algorithm adaptively grows the structure using the observed data using a well defined model selection criteria. The use of polynomial networks was found to provide a structure that is not limited in its approximating capability. This approach was used by Barron et al [52] to provide fault detection, isolation, estimation function and reconfiguration strategies for flight control systems. This paper outlines the design procedure (i.e. database preparation, extraction of wave form features and network synthesis) and the architecture of the system for a control reconfigurable combat aircraft. A similar approach is used in defining an optimum real time, two point boundary value problem for guidance of tactical weapons [53].

Chen and Khalil [54] showed how neural networks may be used to linearize the feedback control problem for non-linear systems. The neural network learned the non-linearities of the system on-line. The output of the controller is then used in a conventional linear control scheme. Fuller et al [55] showed that a nonlinear system could be controlled directly using a neural network as the control element. This was for a simple electronic op amp driven to saturation. However, a comparatively simple neural control was implemented in real time to several hundred hertz.

Jorgensen and Schley [56] discuss the requirements for a neural network based system for an aircraft automatic landing system. It is expected that the flight envelope which is presently very limited may be expanded using such a system. Rather than applying the linear control systems with limited inputs presently in use, a neural network system may be expected to utilize a wide range of input parameters to "learn" the operational responses of pilots in critical situations. Simulations of a sample controller is presented along with the structure of the controller.

An experimental evaluation of neural networks for control of autonomous undersea vehicles is presented by Herman et al [57]. The design of such a system is presented as well as a discussion of the issues relating to intelligent control and the hierarchical control system architecture. An extensive survey of the use of neural networks for the control of other vehicles and robotic motion is included in subsequent chapters of this reference.

The speed and simplicity of neural networks is used by Thursby et al [58] to implement smart electromagnetic structures that provide an adaptive electromagnetic environment to the structure on which they are mounted. By incorporating a neural network into the control structure of a single microstrip patch element, an antenna's performance characteristics may be varied in real time in response to a received signal. This has a payoff of improving receiver characteristics in a frequency agile environment as well as reducing the manufacturing and siting tolerance requirements normally placed on such antennas.

A real-time feedforward neural network controller implemented multiple input, multiple output control of broad band vibration on a built up structure. The controller adaptively learned to control the vibration at multiple sensor locations. Reductions up to 20 dB were attained as reported by Bozich and MacKay [59].

Parker et al [60] describes a broad band controller based on polynomial neural networks to control the vibration generated by the interaction of an elastic structure with both laminar and/or turbulent boundary layers. This works employs recursive elements in a feedback control system to provide control of a stationary random process.

Caball et al [61] use a neural network in an analytical investigation of a nonlinear temporal and spatial optimization problem. The optimum inputs and positions of an array of actuators used for active control of noise transmission are derived. It is shown that this approach is in good agreement with conventional approaches to numerical optimization. Schemes to reduce the required degrees of freedom are illustrated. It is shown that performance of the control system is only marginally affected by the reduced channels in the control system.

Midkiff and McHenry [62] discuss the design of multi-computer networks to meet the processing requirements of smart structures. Methods for mapping neural network computational models onto multi-computer networks are discussed in the context of integrating sensor, control and communication requirements for implementation on real hardware. The structure of the multi-computer processing nodes, interconnection networks and a hierarchical model are studied and alternatives discussed.

Mazzu et al [63] present an approach for the design of intelligent structural monitoring systems. The approach consists of integrating artificial neural networks and knowledge based expert systems in order to achieve maximum benefit from both. In this work, strain measurements are processed through parallel neural networks and expert systems are used to evaluate the results.

Finally, Protzel [64] et al discuss the fault-tolerance of artificial neural networks (ANN). In particular, the fault-tolerance characteristics of time recurrent ANNs that can be used to solve optimization problems are studied. It is demonstrated that although these networks do not perform as well as conventional optimization methods, they perform with a more graceful performance degradation when confronted with various system failures without the additional redundancy required for the conventional systems. This may be especially desirable on long-term, unmanned space missions, where component failures have to be expected but no repair or maintenance can be provided.

4.5 Modeling Requirements for Verification and Simulation

4.5.1 Non-Linear Properties

Joshi [65] presents a concise formulation of relevant nonlinear constitutive relations of piezoelectric materials suitable for sensor and transducer applications. This paper extends the widely accepted linear relations of piezoelectric materials available for structural applications to the electroelastic constitutive behavior that is critical to predicting the response of a structure with embedded piezoelectric materials.

4.5.2 Modeling and Embedment Effect

MIT researchers [66] discuss finite element modeling of ADINA model. Important attributes of the work are one beam element per strut, use of consistent mass matrix, node flexibility incorporated through measured strut component test data, wires modeled as distributed masses, and modal damping included in post processing.

Anderson and Hagood [67] discuss selection of sensors and actuators to minimize impact of model inaccuracies on achievable performance and stability. It is stated that placement and performance/stability are related to the models of the transducers, and method of achieving closed-loop performance or robustness should incorporate model uncertainty information into open or closed loop placement algorithms. Also presented are recent work in the embedded electronics for intelligent structures to establish potential advantages of distributing and embedding large numbers of sensors, actuators and processors for precision control of flexible structures.

Anders and Rogers [68] present an analytical modeling technique which uses the Ritz method, classical laminated plate theory, and finite panel acoustic radiation theory to predict the modal and structural acoustic behavior of locally activated shape memory alloy hybrid composite panels.

Davidson [69] considers the modeling of stress and strain fields around and within optical fibers embedded in carbon reinforced composites. It is stated that the fiber sensor must produce a minimum perturbation in the distribution of reinforcing fibers, not significantly alter the mechanical characteristics of the composite, and match impedance so as not to attenuate sensing signal. Jensen, Pascual, and August [70] present their investigation of the significance of the orientation of embedded optical fibers on the tensile behavior of graphite/bismaleimide laminates. It is reported that optical fibers have a detrimental effect on the tensile behavior of graphite/bismaleimide laminates. Bronowicki, Betros, Nye, McIntyre, Miller and Dvorsky [71] have made mechanical validation of embedded lead-zirconate-titanate (PZT) sensor and actuators in a composite materials. The embedded transducers have been subjected to tension and compression loading at a level of fatigue and to the vacuum and thermal environment of space. Two standard Navy PZT compositions, type I and II, embedded in graphite/epoxy or a graphite/thermoplastic laminate were evaluated.

Bronowicki, Mendenhall, Betros, Wyse and Innis [72] present phase III of the advanced composites with embedded sensors and actuators (ACESA) program.

4.5.3 Simulation and Verification

Wu and Tzeng [73] investigated active vibration control of smart structural materials using the numerical simulation and the experimental testing. The control mechanisms of Lyapunov's second method has been verified to be an effective controller for smart material systems with piezoelectric sensors and actuators for the experimental analysis and the numerical simulation. The piezoelectric active damper is effective for transient vibration control, while it is not sufficient enough to suppress large steady-state oscillation.

Hanks [74] presents ground verification of a large flexible spacecraft and analytical investigation of on-orbit dynamic tests of Space Station Freedom. Difficulties of verifying a large flexible spacecraft on earth are presented with a possible alternative of using scale models to substitute the real model ground tests.

4.5.4 Zero-Gravity Issues

Swanson, Yuen, and Pearson [75] report about the dynamics of test structures on a laboratory suspension system that were compared with the dynamics during zero-gravity parabolic flights on a NASA KC-135 aircraft. It is reported that parabolic aircraft flights can adequately measure the effects of the ground suspension friction and restraint, and that accurate modal measurements can be made. Lawrence, Lurie, Chen and Swanson [76] performed an active member vibration control experiment in a KC-135 reduced gravity environment. The results of flight tests were well correlated to those of the ground tests. Crawley, Alexander and Rey [77] discuss about gravity effects on sensors and actuators, which affect control performance of the system. Both direct and indirect effects of gravity are presented with application to the middeck active control experiment (MACE).

4.5.5 Modal Analysis

Su, Rossi, Knowles and Austin [78] used a digital signal processing (DSP) based workstation to identify modal parameters and vibration control of a cantilever beam. The workstation with DSP as the main processor, it estimated the modal parameters of a cantilever beam after the modes were detected using stochastic methods. The workstation also analyzes the data from 34 piezoceramic sensors of acceleration and strain, and generates control signals to the 18 actuators for vibration control.

4.6 References

1. Jacques, R., Blackwood, G., MacMartin, D., How, J., and Anderson, E., "Control Design For the SERC Experimental Testbeds", MIT Workshop on Control Structures Technology, Jan 22-23, 1992, Cambridge, Mass.

2. Allen, J.J., Lauffer, J.P., and Marek, E.L., "The Sandia Structural Control Experiments," First Joint S.S./Japan Conference of Adaptive Structures, November 13- 15, 1990, Maui, Hawaii.

3. Murotsu, Y., Senda, K., and Hisaji, K., "Optimal Configuration of Control of an Intelligent Truss Structure," First Joint S.S./Japan Conference of Adaptive Structures, November 13-15, 1990, Maui, Hawaii.

4. Hyland, D.C., Collins, E.G., Phillips, D.J., and King, J.A., " Decentralized Control Experiments: Implications for Smart Structures," An International Symposium & Exhibition on Active Materials and Adaptive Structures, November 4-8, 1991, Alexandria, VA.

5. Hong. S.Y., Varadan, V.V., and Varadan, V.K., "Experiments on Active Vibration Control of a thin Plate Using Disc Sensors and Actuators," An International Symposium & Exhibition on Active Materials and Adaptive Structures, November 4-8, 1991, Alexandria, VA.

6. Hanagud, S., Babu, G.L.N., Stalford, H.L., and Won, C.C., "Robustness Issues in the Design of Smart Structures," First Joint S.S./Japan Conference of Adaptive Structures, November 13-15, 1990, Maui, Hawaii.

7. Jacues, Robert N. and Miller, David W., "Preliminary Design of Optimal H-2 and H- infinity Controlled Structures," An International Symposium & Exhibition on Active Materials and Adaptive Structures, November 4-8, 1991, Alexandria, VA.

8. Huang, Chien Y. and Knowles, Gareth J., "Control of Grumman Large Space Structure using H-infinity Optimization, An International Symposium & Exhibition on Active Materials and Adaptive Structures, November 4-8, 1991, Alexandria, VA.

9. Athans, M., Agguiero, F., Bielecki, E., Bokor, J., Douglas, J., and Lublin, L., " Summary of Additional Research in Multivariable Identification and Control," SERC Steering Committee Workshop, January 22-23, 1992, Cambridge, MA.

10. Trent, C.L. and Pak, Y.H., "Control of Space Structures Using Active Piezoelectric Members," An International Symposium & Exhibition on Active Materials and Adaptive Structures, November 4-8, 1991, Alexandria, VA.

11. Sekine, K., Shibayama, Y., Iwasawa, N., Tagawa, N., Sunahara, S., Yoshida, s., and Arikabe, T., "Identification and adaptive Control of Flexible Truss Structures," First Joint S.S./Japan Conference of Adaptive Structures, November 13-15, 1990, Maui, Hawaii.

12. Melcher, J. and Wimmel, R., " Modern Adaptive Real-Time Controller for Actively Reacting Flexible Structures," First Joint S.S./Japan Conference of Adaptive Structures, November 13-15, 1990, Maui, Hawaii.

13. Maghami, Peiman G., Joshi, Suresh M., and Price, Douglas B., "Integrated Controls- Structures Design Methodology for a Flexible Spacecraft," 15th Annual AAS Guidance and Control Conference, February 8-12, 1992, Keystone, CO.

14. Maghami, P.G., Joshi, S.M., and Lim, K.B., "Integrated controls-Structures Design: A Practical Design Tool for Modern Spacecraft," 1991 American Control Conference, June 26-28, 1991, Boston, MA.

15. Maghami, P.G., Joshi, S.M., Walz, J.E., and Armstrong, E.S., "Integrated Controls-Structures Design Methodology Development for a Class of Flexible Spacecraft," Third Air Force/NASA symposium on Recent Advances in Multi-disciplinary Analysis and Optimization, September 24-26, 1990, San Francisco, CA.

16. Maghami, P.G., Joshi,S.M., and Gupta, S., "Integrated Controls-Structures Design for a Class of Flexible Spacecraft," Fourth NASA/DoD CSI Technology Conference, November 5-7, 1990, Orlando, FL.

17. Iwatsubo, T., Kawamura, S., Adachi, K., and Ikeda, M., "Simultaneous Optimum Design of Structural and Control System," First Joint S.S./Japan Conference of Adaptive Structures, November 13-15, 1990, Maui, Hawaii.

18. Widrow, B. and Stearns, S.D. "Adaptive Signal Processing", Prentice-Hall, Englewood Cliffs, N.J. 1985.

19. Widrow, B. et al: "Adaptive Noise Canceling:Principles and Applications," Proc. of the IEEE, vol 63, no. 12, Dec. 1975.

20. Widrow, B. and Hoff, M.E.;"Adaptive Switching Circuits,"IRE WESCON Convention Rec. Pt. 4, pp 96-104,1960.

21. Burgess, J.C.,"Active Adaptive Sound Control in a Duct: A Computer Simulation," J. Acoust. Soc. Amer., vol 70, pp 715-726, 1981.

22. Lueg, P.;"Process of Silencing Sound Oscillations," U.S. Patent no. 2,043,416, Filed: March 8, 1934, Patented: June 9, 1936.

23. Olsen, H.F. and May, E.G.;"Electronic Sound Absorber," Jour. Acoust. Soc. Am. vol. 25(6) pp 1130-1136, 1953.

24. Ffowcs-Williams, J.E.: "Anti-sound," Proc. R. Soc. Lond. A 395, 63-88, 1984

25. Warnaka, G. "Active Attenuation of Noise - State of the Art,"Noise Control Engineering, pp 100-109, vol. 18(3), May-June 1982.

26. Elliott, S.J., Stothers, I.M. and Nelson, P.A.: "A multiple Error LMS Algorithm and Its Application to the Active Control of Sound and Vibration" IEEE Trans. on Acoustics, Speech and Signal Processing, Vol. ASSP-35, No. 10, October 1987.

27. Elliott, S. J. and Darlington, P.: "Adaptive Cancellation of Periodic, Sychronously Sampled Interference" IEEE Trans. on Acoustics, Speech and Signal Processing, Vol. ASSP-33, No. 3, June 1985.

28. Johnson, C.R.; "Adaptive IIR Filtering: Current Results and Open Issues," IEEE Trans. on Information Theory, vol. IT-30, no.2, March 1984.

29. Eriksson, L.J.; "Development of the filtered-U algorithm for active noise control," J. Acoustical Soc. Amer. vol. 89(1), January 1991.

30. Ross, C.F.; "An Adaptive Digital Filter for Broadband Active Sound Control," J. Sound and Vibration, vol. 89, pp 381-388, 1982

31. Roure, A.; "Self-Adaptive Broadband Active Sound Control System," J. Sound and Vibration, vol.101, no. 3, pp 429-441.

32. Silcox, R. J.; "Frequency Domain Adaptive Algorithms for Active Control," Proc. Internoise 91, pp 173-176, Sydney, Australia, 2-4 Dec, 1991.

33. Bullmore, A.J. et al; "Models for Evaluating the Performance of Propeller Aircraft Active Noise Control Systems," AIAA paper no. 87-2704

34. Silcox, R.J., Fuller, C.R., and Lester, H.C.; "Mechanisms of Active Control in Cylindrical Fuselage Structures," AIAA Journal, vol 28, no 8, August 1990.

35. Elliott, S.J. et al; "In-flight Experiments on the Active Control of Propeller-Induced Cabin Noise," J. of Sound and Vibration, vol. 140(2), pp219-238, 1990.

36. Dorling, C.M. et al;"A demonstration of active noise reduction in an aircraft cabin,"Jour. of Sound and Vibration, vol. 128(2), January 22, 1989.

37. C.R. Fuller and J.D. Jones, "Experiments on Reduction of Propeller Induced Interior Noise by Active Control of Cylinder Vibration", J. Sound Vib. 112(2), 389 (1987)

38. M. Simpson et al, "Full Scale Demonstration of Cabin Noise Reduction using Active Vibration Control", AIAA J. Aircraft 28(3), 208 (1991).

39. C.R. Fuller et al, "Active Control of Interior Noise in Model Aircraft Fuselages Using Piezoelectric Actuators", AIAA Paper no. 90--3922 (1990)

40. R.J. Silcox et al, "Evaluation of Piezoceramic Actuators for Control of Aircraft Interior Noise", presented at 14th AIAA Aeroacoustics Conf. May 1992, AIAA paper no. 92-02-091.

41. V.R. Sonti and J.D. Jones, Proc of Recent Advances in Active Control of Sound and Vibration, Blacksburg, VA (Technomic Press, PA) 27 (1991)

42. H.C. Lester and S. Lefebvre, Proc of Recent Advances in Active Control of Sound and Vibration, Blacksburg, VA (Technomic Press, PA) 3 (1991)

43. C. R. Fuller, "Active Control of Sound Transmission/Radiation from Elastic Plates by Vibration Inputs, I: Analysis", J. Sound Vib. 136(1), 1 (1990)

44. V.L. Metcalf et al, "Active Control of Sound Transmission/Radiation from Elastic Plates by Vibration Inputs, II: Experiments", J. Sound Vib. 152(3) (1992)

45. R.L.Clark and C.R. Fuller, Proc of Recent Advances in Active Control of Sound and Vibration, Blacksburg, VA (Technomic Press, PA) 507 (1991)

46. C. R. Fuller, C.A. Rogers and H.H. Robertshaw, "Active Structural Acoustic Control with Smart Structures", Proc. of SPIE Conf., vol. 1170, 338 (1989)

47. Y. Gu and C. R. Fuller, "Active Control of Sound Radiation from a Uniform Rectangular Fluid-Loaded Plate", J. Acoust. Soc. Am. 89(4) Pt.2, 1915 (1991)

48. Werbos, P.J. "Backpropagation: past and future," proceeding of IEEE International Conference on Neural Networks, IEEE Press, I:343-353, 1988.

49. Narendra, K.S. and Parthasarathy, K.; "Gradient Methods for the Optimization of Dynamical Systems Containing Neural Networks," IEEE Trans on Neural Networks, vol. 2, no.2, pp 252-262, March 1991.

50. Hoskins, D.A. and Vagners, J.; "A Neural Network Based Explicit Model Reference Adaptive Controller," proc. 29th Conf. on Decision and Control, Honolulu, Hawaii, pp. 1725-1729, Dec. 1990.

51. Barron, A.R. and Barron, R.L. "Statistical Learning Networks: A Unifying Approach," Computing Science and Statistics: 1988 Proc. of the 20th Symposium on the Interface, pp 192-203.

52. Barron, R.L. et al, "Application of Polynomial Neural Networks to FDIE and Reconfigurable Flight Control," National Aerospace Electronics Conference, Dayton OH, May 23-25, 1990.

53. Barron, R.L. and Abbott D.W.; "Use of Polynomial Networks in Optimum, Real Time, Two-Point Boundary Value Guidance of Tactical Weapons," presented at Military Computing Conference, May 3-5, 1988, Anaheim, CA.

54. Chen, F.C. and Khalil, H.K.; "Adaptive Control of Non-Linear Systems Using Neural Networks," proc. 29th Conference on Decision and Control, pp 1707-1712, Honolulu, Hawaii, Dec. 1990.

55. Fuller, C.R., Caball, R. and Brown, D.; proc. Internoise 91, Sydney, Australia, Dec. 1991.

56. Jorgensen C.C. and Schley, C.; "A Neural Network Baseline Problem for Control of Aircraft Flare and Touchdown," pp. 403-425, Neural Networks for Control, MIT Press, Cambridge MA 1990.

57. Herman,M. et al; "Intelligent Control for Multiple Autonomous Undersea Vehicles," pp. 427-474, Neural Networks for Control, MIT Press, Cambridge MA 1990.

58. Thursby, M. et al; "Neural Control of Smart Electromagnetic Structures," proc. of An International Symposium & Exhibition on Active Materials & Adaptive Structures, Alexandria VA, Nov 1991.

59. Bozich, D.J. and MacKay, H.B.; "Neurocontrollers Applied to Real-Time Vibration Cancellation at Multiple Locations," Proc. of Conf. on Recent Advances in Active Control of Sound and Vibration, pp 326-337, VPI&SU, Blacksburg, VA April 1991.

60. Parker, B.E. et al; "Adaptive Nonlinear Polynomial Neural Networks for Control of Boundary Layer/Strucutral Interaction," NASA CR-189645, 1992.

61. Caball, R. et al; "The Optimization of Force Inputs for Active Structural Acoustic Control using a Neural Network," NASA TM-107627, 1992.

62. Midkiff, S.F. and McHenry, J.T.; "Multicomputer Networks for Smart Structures," Proc. of An International Symposium & Exhibition on Active Materials & Adaptive Structures, Alexandria VA, Nov 1991.

63. Mazzu, J.M., Allen, S.M. and Caglayan, A.K.; "Neural Network/ Knowledge Based Systems for Smart Structures," Proc. of An International Symposium & Exhibition on Active Materials & Adaptive Structures, Alexandria VA, Nov 1991.

64. Protzel, P.W., Palumbo, D.L. and Arras, M.K.; "Performance and Fault-Tolerance of Neural Networks for Optimization," NASA CR-187582, ICASE Report No. 91-45. June 1991.

65. Joshi, S.P., "Nonlinear Constitutive Relations for Piezoceramic Materials," An International Symposium & Exhibition on Active Materials and Adaptive Structures, November 4-8, 1991, Alexandria, VA.

66. How, J.P., Blackwood, B., Anderson, E., and Balmes, E., "Finite Element Model and Identification Procedure",SERC Steering Committee Workshop, Jan 22-23, 1992, Cambridge, MA.

67. Anderson, E. and Hagood, N.W., "Sensor and Actuator Technology Development," SERC Steering Committee Workshop, January 22-23, 1992, Cambridge, MA.

68. Anders, W.S. and Rogers,C.A., "Vibration and Low Frequency Acoustic analysis of Piecewise-Activated Adaptive Composite Panels," First Joint S.S./Japan Conference of Adaptive Structures, November 13-15, 1990, Maui, Hawaii.

69. Davidson, R., "Do Embedded Sensor systems Degrade Mechanical Performance of Host Composites?" An International Symposium & Exhibition on Active Materials and Adaptive Structures, November 4-8, 1991, Alexandria, VA.

70. Jensen, D.W., Pascual, J., and August, J.A., "Tensile Strength and stiffness Reduction Graphite/Bismaleimide Laminates with Embedded Fiber Optic Sensors," An International Symposium & Exhibition on Active Materials and Adaptive Structures, November 4-8, 1991, Alexandria, VA.

71. Bronowicki, A., Retros, R., Nye, T., McIntyre, L., Miller, L., and Dvrosky, G., "Mechanical Validation of Smart Structures," SDIO Workshop on Advanced Piezoelectric Actuation Materials for Space Applications", Institute for Defense Analyses, Feb. 25, 1992, Alexandria, VA.

72. Bronowicki, A.J., Mendenhall, T.L., Betros, R.S., Wyse, R.E., and Innis, J.W., " ACESA Structural Control System Design," First Joint S.S./Japan Conference of Adaptive Structures, November 13-15, 1990, Maui, Hawaii.

73. Wu, W.B. and Tzeng, M.J., " Active Vibration Control of Smart Structural Materials," First Joint S.S./Japan Conference of Adaptive Structures, November 13-15, 1990, Maui, Hawaii.

74. Hanks, B.R., "Research on the Structural Dynamics and Control of Flexible Spacecraft," An International Symposium & Exhibition on Active Materials and Adaptive Structures, November 4-8, 1991, Alexandria, VA.

75. Swanson, A.D., Yuen, W., and Pearson, J., "Zero-Gravity Dynamics of Space Structures in Parabolic Aircraft Flight," First Joint S.S./Japan Conference of Adaptive Structures, November 13-15, 1990, Maui, Hawaii.

76. Lawrence, C.R., Lurie, B.J., Chen, G-S., and Swanson,A.D., "Active Member Vibration Control Experiment in a KC-135 Reduced Gravity Environment," First Joint S.S./Japan Conference of Adaptive Structures, November 13-15, 1990, Maui, Hawaii.

77. Crawley, E.F., Alexander, H., and Rey, D., "The Middeck Active Control Experiment: Gravity and Suspension Effects," SERC Steering Committee Workshop, January 22-23, 1992, Cambridge, MA.

78. Su, J., Rossi, M., Knowles, G., and Austin, F., "Piezoceramic/DSP-Based Integrated Workstation for Modal Identification and Vibration Control," An International Symposium & Exhibition on Active Materials and Adaptive Structures, November 4-8, 1991, Alexandria, VA.

5 Recommendations for Future Research

The recommendations for future research in active (smart) structures at Langley emphasize Langley's strengths so that significant contributions might be achieved. The recommendations are in the following areas:

1) actuation materials
2) smart/intelligent sensors
3) information management
4) applications

5.1 Actuation Materials

In the materials area, the integration of smart materials such as piezoelectric ceramics into composite materials is seen as a research area in which Langley can make significant technical contributions. By incorporating the sensing and actuation function within the composite material, weight reductions, decreased volumes, increased reliability (fewer parts) and improved performance (better sensing and actuation) may be achieved in future aircraft and spacecraft designs. Potential research areas are piezoelectric polymeric films and coatings, integration of piezoelectric ceramic powders and metallic powders into composites, and piezoelectric fibers. The use of magnetostrictive materials, such as Metglas and Terfenol-D, with composites is another research area that should be pursued. These magnetostrictive materials have large force outputs and use low voltage inputs.

Piezoelectric ceramic powders and polymers may be film cast into thin sheets for various applications. Likewise, Terfenol-D powder and polymers could also be film cast for applications in various structural concepts.

More ways of integrating sensing materials into composites needs to be investigated. This would allow for more and better information about the structural environment that could lead to improved performance and understanding of structural behavior.

For aircraft, the current designs use the lightest materials and strongest configurations available. A goal of these smart actuation materials should be to develop stiffnesses comparable to current engineering materials.

5.2 Smart/Intelligent Sensors

Any intelligent aspect of a smart structure should come from its ability to receive and process external disturbances and command actuators based upon a control strategy resident in the control processors. A smart structure can only be as smart as its built-in intelligence level.

Areas of smart sensors which are applicable to various aspects of parameter measurements should be pursued, such areas as, acceleration, strain and strain rate, force, pressure, temperature and displacement. These measurands should be converted to signals that are suitable for signal processing and subsequent communication to the smart structure information management system.

The use of smart sensors to measure pressure and loads on wing surfaces during wind tunnel tests and flight tests should be pursued. In wind tunnel testing, the use of smart sensors could reduce the cost of design and fabrication.

5.3 Information Management

The networking of smart structural subsystems within a structure is seen as a very important research area which has not received attention by researchers. Concepts need to be developed and evaluated for performance and applications. A general architecture for information management is needed within which the network resides. Research in smart/intelligent structures at this time has dealt with a single system or subsystem. Some understanding of how these subsystems will be integrated on an aircraft or spacecraft should be addressed. It is possible that individual autonomous smart subsystems could give conflicting commands to cause performance to degrade. Thus an overall information management system including the networking architecture should be developed.

5.4 Applications

It is hoped that the development of new smart materials and the supporting technologies (electroding, poling and testing) will form a critical mass of people capable of interfacing with other researchers here at the Center. The exchange of ideas is important and we can only suggest a few ways in which smart materials could be used in aircraft and spacecraft.

In aircraft the use of smart materials in aircraft wing designs can be used to suppress flutter, control winglets, change control surfaces, and extend laminar flow region. It may be possible to develop a gust load alleviation system for general aviation. Improved sensing of performance related parameters in aircraft wings should be emphasized. Use of new smart materials should be pursued for noise suppression in transports.

Force balances for supporting wind tunnel models could benefit from the smart materials area. A single variable stiffness support could accommodate the testing requirements of different size models which have different load ranges. This would allow other components to be properly sized so that the measured force and moments are sensitive to the wind induced loads.

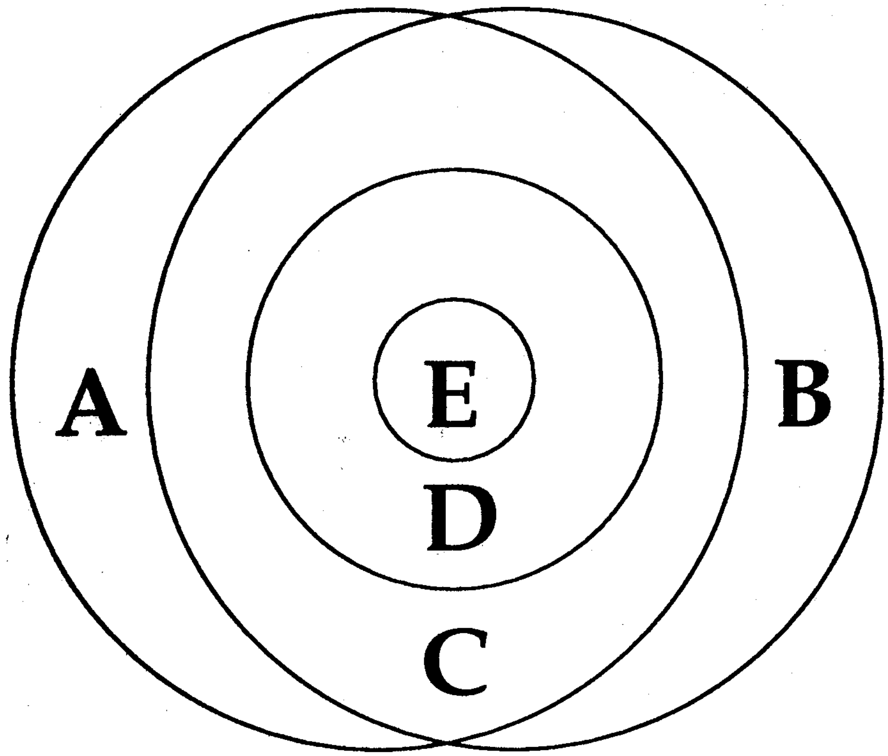
5.5 Research Environment

A strong requirement for implementation of innovative structural systems is an understanding of the physics of the system to be controlled. The advanced structural dynamic modeling capabilities at Langley provide a firm foundation for future development. Additionally, for aeronautical applications, dynamic modeling of fluid structural coupling effects should be emphasized for innovative applications of smart structures.

It is hoped that a coordinated effort in active structures will be more formally established here at the Center. The research areas discussed in this report are multi-disciplinary and require the cooperation of several organizations. With research activities in aeronautics and space at the Center, the management could help foster the research environment by advising the active structures technical committee of research in their organization in active structures. It would then be the intention of the technical committee to have the researcher present his or her results and engage in an exchange of ideas.

Appendix A

Proposed Structure Types



A	**Sensory**
B	**Adaptive**
C	**Controllable**
D	**Active**
E	**Intelligent**

Piezoelectric Materials

Piezoelectric material are materials which generate a mechanical strain when an electrical voltage is applied or vice versa generate an electrical voltage when they are mechanically deformed. There are manmade materials which may be poled such that they will exhibit piezoelectric properties. This is accomplished by applying a large inducing voltage across the material. The dipoles within the material align themselves such that the positive ends of the dipoles are oriented toward the negative poling voltage. The electric field is held on the material for a certain time and then removed. The dipoles maintain their orientation. When subsequent smaller voltages are applied to the same piece of material, the dipoles will respond by attempting to reorient themselves.

To utilize the material once it has been poled, a charge is applied across the material. The dipoles within the piezoelectric ceramic will attempt to align themselves such that the positive ends of the dipoles will be attracted by the negative applied current and vice versa.

The electromechanical coupling coefficient is called d, followed by subscripts. The first subscript corresponds to the direction of the applied voltage and the second corresponds to the direction of deformation.

Figure 1 shows the electrodes attached to the ceramic in the same manner as the original inducing voltage was applied. This is the 3-direction. The in-plane directions are defined as the 1 and 2 -directions. When the voltage is applied as shown in the figure, the negative ends of the dipoles are pulled by the positive voltage and the positive ends are pulled by the negative voltage. This causes a stretching of the material in the direction of poling. The figure on the left shows this effect, which is termed the d_{33} effect.

Figure 2 illustrates that in response to a voltage applied in the 3-direction, a deformation occurs in the in-plane direction. Note that the d_{33} and d_{31} effects occur simultaneously. The d_{31} effect can be thought of as a Poisson-like effect.

Figure 3 shows the d_{15} effect which occurs when the electrodes and thus the applied voltage are oriented at 90 degrees to the direction of the polarization. The resultant deformation is a shear effect as the tops of the dipoles pull to the left and the bottoms strain to the right.

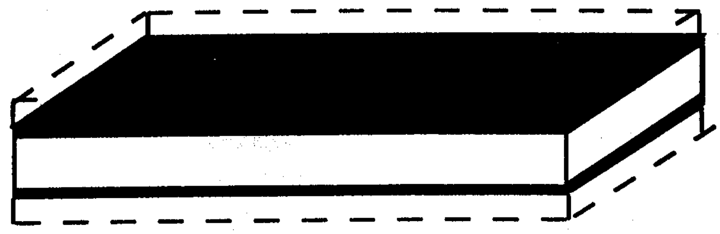


Figure 1 Thickening Effect (d_{33}effect)

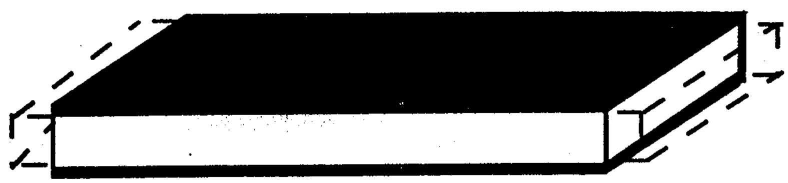


Figure 2 Lengthening Effect (d_{31}, d_{32}effect)

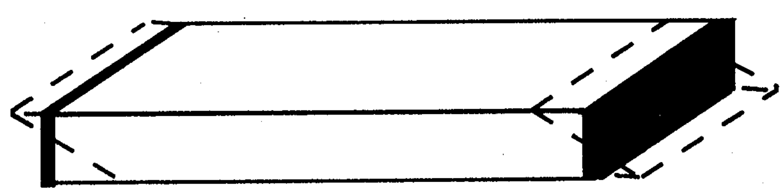
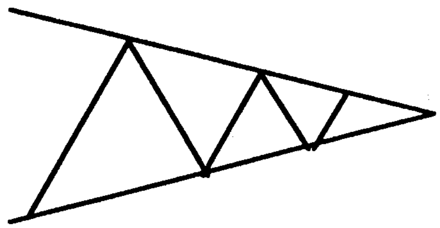


Figure 3 Shearing Effect (d_{15} effect)

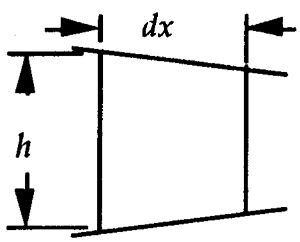
Effect of Expansion and Contraction of the Surfaces on Shape of a Wedge-Shaped Trailing Edge

A very effective means of control for subsonic airplanes is deflection of the trailing edge of an airfoil. Determination of the effect of expansion and contraction of the skins on the shape of a trailing edge is therefore of interest. A means of accomplishing the expansion and contraction could be a surface mounted piezoelectric ceramic.

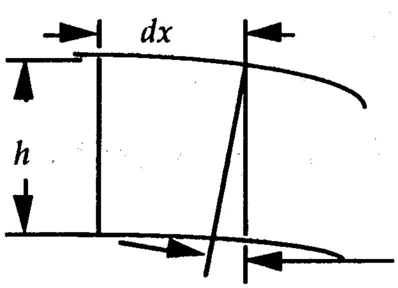
Consider a trailing edge with flat upper and lower surfaces. The skins can expand or contract longitudinally. As shown in the following sketch, the interior structure may be considered to be a Warren truss that resists shear but offers no resistance to expansion or contraction of the skins.



An element of the trailing edge of height h and length dx is shown below:



If the upper surface expands and the lower surface contracts, the change in length of each surface element is plus or minus sdx, where s is the strain of each surface. The change in angle of the rear of the section as a result of this deformation is



$$\Delta\alpha = -\frac{2s}{h}dx$$

The thickness of the wedge-shaped trailing edge is defined by the formula:

$$h = h_0 - Kx = h_0 - \frac{h_0}{x_m}x = \frac{h_0}{x_m}(x_m - x)$$

If this value is substituted the preceding expression, then the slope of the mean line may be determined by the expression:

$$\Delta\alpha = -\frac{2sdx}{h_0/x_m(x_m - x)}$$

Integrating this expression:

$$\alpha = -\frac{2s}{h_0/x_m}\int_0^{x_i}\frac{dx}{(x_m - x)}$$

or

$$\alpha = \frac{dy}{dx} = \frac{2s}{h_0/x_m} ln\left(\frac{x_m - x}{x_m}\right)$$

the displacement is then:

$$y = \int\frac{dy}{dx}dx = \frac{2s}{h_0/x_m}\int_0^{x_i} ln\left(\frac{x_m - x}{x_m}\right)dx$$

let

$$u = \frac{x_m - x}{x_m},\ du = -\frac{dx}{x_m},\ or\ dx = -x_m du$$

then

$$y = \frac{2s}{h_0/x_m}(-x_m)\int_1^{\frac{x_m - x_i}{x_m}} ln(u)du$$

$$= \frac{2s}{h_0/x_m}(-x_m)\left[u\,ln(u) - u\right]_1^{\frac{x_m - x_i}{x_m}}$$

$$= \frac{2s}{h_0/x_m}(-x_m)\left[\frac{x_m - x_i}{x_m} ln\left(\frac{x_m - x_i}{x_m}\right) - \frac{x_m - x_i}{x_m} - (ln(1) - 1)\right]$$

simplifying:

$$\frac{y}{x_m} = -\frac{2s}{h_0/x_m}\left[\left(1-\frac{x_i}{x_m}\right)ln\left(1-\frac{x_i}{x_m}\right)+\frac{x_i}{x_m}\right]$$

A plot of 2 times the quantity in brackets (for $0 \le x_i/x_m \le .9$) is shown in figure 1.

Discussion

The mean line is seen to bend with increasing slope as the trailing edge is approached. In practice, the finite thickness of the trailing-edge skin would prevent the use of this theory too close to the trailing edge. Also, the small angle approximations made in the derivation become invalid when the slope is too large. In the case of no small-angle approximations and the mathematical idealization of infinitely thin skin, an exact solution would show the mean line spiraling around an infinite number of times as the trailing edge is approached. This behavior is an interesting example of Zeno's paradox, but has no practical significance.

As an example, consider the trailing edge to be rigid (because of finite skin thickness) for the rear 10 percent of the wedge-shaped section considered. Then, as shown in figure 1 (with a linear function from $.9 \le x_i/x_m \le 1$ which is tangent to the curve at the point $x_i/x_m = .9$), the deflection at the trailing edge would be approximately:

$$\frac{y}{x_m} = -1.8\frac{s}{h_o/x_m}$$

For a value of $h_o/x_m = 0.1$ and a value of $x_m = 1$ foot, the value of y at the trailing edge would be as follows for several values of the strain, s.

s	y, in.
0.01	2.16
0.001	0.216
0.0001	0.0216

A value of strain of about 0.01 would be required with the method studied to give a trailing-edge deflection comparable to that obtained with a conventional control surface.

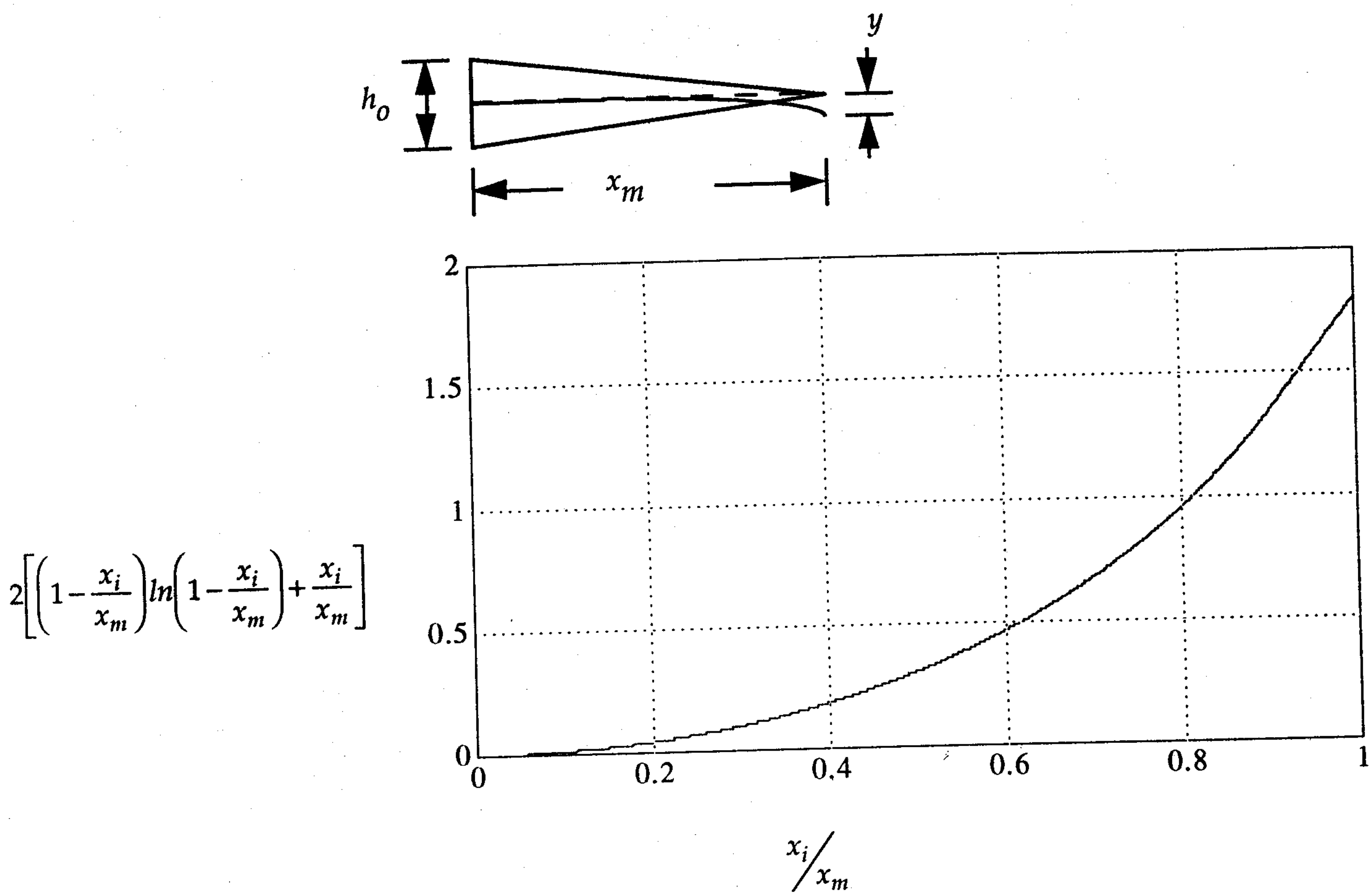


Figure 1 Function showing shape of mean line of trailing edge caused by expansion and contraction of surfaces

Comparisons of Adaptive Materials

The following information was presented by Dr. Ralph Fenn of SatCon Technology Corp. at NASA Langley Research Center on February 6, 1992.

Qualitative Comparison of Adaptive Materials

Magnetostrictive foil is superior to piezoelectric ceramics in four areas.

1. RELIABILITY:
o No inaccessible embedded leads to break.
o Physical continuity of large electrodes is not required.
o Minimized short circuits due to conductive laminations.
o Low voltage power improves reliability.

2. STABLE PROPERTIES:
o Low temperature sensitivity of magnetostriction.
o Low creep.
o No "bleeding" like piezoelectrics where initial elongation decays.
o Will not depole or break down like piezoelectric materials in high operating fields.

3. MANUFACTURABILITY:
o Tough Metglas ribbon can be wound onto mandrels at high speed.
o Pre-anneal Metglas is flexible enough to follow very tight curves.
o Interlacing of electrodes and active material is not required so process is simpler.

4. FLEXIBILITY:
o Adaptive material shape response can be altered by changing field shape using interchangeable coils.

Quantitative Comparison of Adaptive Materials

	PZT G-1195 Piezoceramic	PVDF Piezo Film	PMN-BA Electrostr.	Nitinol Shp Mem.	Terfenol-D Magnetostr.
Max. Strain (ppm)	300	300	600	20000 AC	1800
E $(lb/in^2) \times 10^{-6}$	9	0.3	17	8	7
T max (°C)	360	100	high	45	380
Hysteresis (%)	10	>10	<1	5	2
Bandwidth	kHz	kHz	kHz	1 Hz	100 Hz
Temp. Sen.(%/°C)	0.05	0.8	0.9	-	0.3

Comparison of Magnetostrictive Materials

	Nickel	Metglas	Terfenol-D
Maximum strain	50 ppm	50 ppm	1800 ppm
Field required	6,000 G	1 G	500 G
Resistivity	$7 \times 10^{-8}\ \Omega m$	$1 \times 10^{-6}\ \Omega m$	$6 \times 10^{-7} \Omega m$
Available in foil	yes	yes	no

Conclusions:

1. Nickel and most magnetostrictive materials require large fields for actuation.

2. Metglas has same maximum strain as traditional magnetostrictive materials but requires three orders of magnitude lower fields.

3. Terfenol-D has 35 times larger strains than Metglas but can not be laid into composites.

Typical Applications of Piezoelectric Film (PVDF)

COMPUTER INPUT/OUTPUT

Keyboards
- Keypads and Arrays

X-Y Coordinates
- Digitizer
- Interactive Touch Screen
- Mouse
- Joystick

Printers
- Impact Flight Time
- Ink Drop Generation and Detection

Copiers
- Switches
- Paper Path Switches
- Toner Level

Disc Drives
- Accelerometers
- Ferroelectrlc Memory

INDUSTRIAL

Switches
- Solid State
- Snap Action
- Cantilever Beam
- Keypad/Keyboard
- Vandal-Proof
- Intrinsically Safe
- CMOS Wake-up
- Low-Deflection
- Singing Switch
- Coin Counter
- Acoustic Switch
- Shaft Rotation
- Magnetic Reed

Physical Security Energy Management
- 180 Degree Passive Infrared Sensors
- Vidicon
- Glass Break Detectors
- Floor/Mat Sensor (STEP SWITCH II)
- Penetration Detection
- Contact Microphone
- Piezo Cable Perimeter Protection
- Pyrometer/Flame Sensor

Robotics
- Tactile Sensor
- Micropositioner
- Safety Mats & Switches
- Bumper Impact

Fans
- Solid State
- Microfan

Flow/Level
- Vortex
- Fluidic Oscillator
- HVAC Air Flow
- Doppler Ultrasound
- Solid State Fluid Level
- Densometer
- Laminar/Turbulent Boundary Layer

INSTRUMENTATION

Machine Health Monitor
- Accelerometers
- Contact Microphones
- Hi-Strain Dynamic Strain Gages

Weather Sensors
- Rain Intensity
- Hall Detection
- Wind Velocity

Defouling
- Hull
- Water Supply

Active Vibration Damping
- Strain Gages Sensor Arrays
- Actuator Arrays

Non Destructive Eng.
- Flexible Contact NDT Probes for Composites
- NDT Arrays
- Acoustic Emission Sensors

Air Ranging Ultrasound

Safety
Speed
Distance

Adaptive Optics
Fiber Optic Shutters/Modulators
Deformable Mirrors
Laser Scanners

Oil Exploration
Hydrophones
Seismic Geophones

Membranes
Active (Defouling) Membranes

Micropositioners
Tactile Microgrippers
Micromotors
Micropumps
Microfans

Power Generation
Ocean Wave
Wind Energy
Photoelectric (Solar)

MEDICAL

Diagnostics
Apnea Monitor
Ambulatory/Gait Monitors
Blood Pressure Cuff
Pressure Point Mattress
Pulse Counter
Stethoscope
Sleep Disorder Monitors
Respiratory Air Flow
Instant Thermometer
Isokinetics

Therapy
Transdermal Drug Administration
Pressure Ulcer Therapy
Osteogenesis
Wound Healing
Nerve Regeneration

Ultrasound
Near Field Imaging
Prostate
Transdermal
Transluminal
Coronary Arterial
Breast
Lithotripter
Hydrophone Calibration Probes

Handicapped Aides
Switches
Prosthesis
Braille Reader
Hearing Aid
Speech Intensification

Biological and Chemical
Thermometrlc Bioanalytical Sensors

Sample Analysis
Mass Change Measurement
Reactive Microstrain Measurement

Implantables
Pacemaker Activity Monitor
Implantable Switch
Vascular Graft Monitor
Micropump
Artery Monitor
Micropower Source

Instrumentation
Intravenous Drop Counter
IV Air Bubble Detection
Laser Switch/Modulator

TELECOMMUNICATIONS

Keyboard, Microphones, Speakers, Security
Keypads, Hook switches
Handset, Squawk-box
Headset, Credit Card
Tone Generators
Cable Security

AUTOMOTIVE

Air Bag
Crash Sensor
Crush Sensor
Accelerometer
Occupancy Seat Sensor

Suspension
Active Suspension

Switches
Passenger Compartment Switches

Horn Switch
Control Panel

Fuel Level, Tire Rotation, Security
Keyless Entry
Motion (theft) Sensor
Passive Infrared Sensor

CONSUMER

Musical Instruments
Pick-up
Drum Trigger

Sports Equipment
Target Location (Baseball, Golf, Tennis, Basketball, etc.)
Speed
Reaction Time
Foul Line
Force (Karate Impact, Football Sled, Jump Force)
Sweet Spot

Toys/Games
Switches
Proximity (Passive Infrared)

Audio
Tweeter
Balloon Speakers
Novelty Speakers (Visor, Poster)
Microphone

MILITARY/GOVERNMENT

Hydrophones
Towed Cable Array
Hull Mounted Arrays
Sonobuoys
Active Noise Suppression

Ballistics
Safety and Arming Fuses
Shock Wave Gages
Detonators
Target Coordination Detection
Smart Munition Pyroelectric Sensors
Seismic Accelerometers

Physical Security
Perimeter
Seismic/Geophones
Covert Microphones

Traffic Sensors
Vehicle Classification
Weight-In-Motion
Speed
Lane Designation
Toll Booth

Appendix F

Typical Properties of Piezoelectric Film (PVDF)

Thickness	9,28,52,110 x 10^{-6} meter
Piezoelectric Strain Constant - d_{31}	23 x 10^{-12} $\frac{m/m}{V/m}$
Piezoelectric Strain Constant - d_{33}	-33 x 10^{-6} $\frac{m/m}{V/m}$
Piezoelectric Stress Constant - g_{31}	216 x 10^{-3} $\frac{V/m}{N/m^2}$
Piezoelectric Stress Constant - g_{33}	-339 x 10^{-3} $\frac{V/m}{N/m^2}$
Electromechanical Coupling Factor	12% (@ 1 kHz) 19% (@1 kHz)
Capacitance	380 pF/cm^2 for 28 x 10^{-6} meter film
Young's Modulus	2 x 10^9 n/m^2
Speed of Sound	1.5 - 2.2 x 10^3 m/s (transverse thickness)
Pyroelectric Coefficient	-25 x 10^{-6} $C/m^2{}^\circ K$
Permittivity	106 - 113 x 10^{-12} F/m
Relative Permittivity	12 - 13
Mass Density	1.78 x 10^3 kg/m^3
Volume Resistivity	10^{13} ohm meters
Surface Metallization Resistivity	2.0 ohms/square for CuNi 0.1 ohms/square for Ag ink
Loss Tangent	0.015 - .02 (@ 10 - 10^4 Hz)
Compressive Strength	60 x 10^6 N/m^2 (stretch axis)
Tensile Strength	160 - 300 x 10^6 N/m^2 (Transverse axis)
Temperature Range	-40°C to 80°C
Water Absorption	< 0.02% H_2O
Max. Operating Voltage	750 V/mil = 30 V/10^{-6}m
Breakdown Voltage	2000 V/mil = 100V/10^{-6}m

Measured and calculated properties of (Pb, Ca)TiO_3 ceramic and stycast composites

Contains 25 percent ceramic by volume. Underlined quantities are measured directly. Others are inferred.

	Ceramic Measured	Composite	
		Meas'd	Calc'd
e^t_{33}	<u>207</u>	<u>55</u>	55
d_{33} (pC/N)	<u>70</u>	<u>49</u>	57
d_{31} (pC/N)	<u>-2.4</u>	<u>-8.5</u>	-13
k_{31} (%)	<u>2.1</u>	<u>4.9</u>	6.8
d_h (pC/N)	<u>65</u>	<u>32</u>	31
g_h (MV-m/N)	35	66	64
$d_h g_h (10^{-15} m^2/N)$	2280	2100	1980

Appendix H

Piezoelectric Properties

Sample	Rod diced from[1] Sintered Pellet	Rod #1	Composite N-1	Composite #2
Size	1mm x 1mm	Dia. 0.8mm	Dia. 30mm	Dia. 4mm
Density (g/cm^3)	7.4	7.5	1.8	3.62
Dielectric Constant, K_{33}^T	3200	3000	320	420
d_{33} (pC/N)	593	610	400 on Rod 230 between Rod	310
K_{33} (K_t)	0.75[2]	0.65	0.55	0.61
C^D (m/s)			2800	3520
d_h (pC/N)			40	52
g_h (10^{-3}vm/N)			14[3]	14[3]
Impedance (MRayl)			5.0	12.7

1 Data from FMI, parts fabricated by Vernitron
2 Data from Vernitron literature
3 Constant up to hydrostatic pressure 1050 PSI, equipment limit

Fatigue Loading Schedules

Type-Schedule	Load lb	Strain m-e	Percent of Limit	Number of Cycles
1-a	1,500	360	60%	100
1-b	2,500	600	100%	10
	2,000	480	80%	50
	1,500	360	60%	800
11-a	4,200	900	60%	100
11-b	7,000	1,500	100%	10
	5,600	1,200	80%	50
	4,200	900	60%	800

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1992	Technical Memorandum

4. TITLE AND SUBTITLE
A State-of-the-Art Assessment of Active Structures

5. FUNDING NUMBERS
WU 590-14-41

6. AUTHOR(S)
Active Structures Technical Committee

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-0001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-107681

11. SUPPLEMENTARY NOTES
Garnett Horner, Chairperson, Active Structures Technical Committee, Langley Research Center, Hampton, Virginia

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited

Subject Category 39

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

This report is a state-of-the-art assessment of active structures with emphasis towards the applications in aeronautics and space. It is felt that since this technology area is growing at such a rapid pace in many different disciplines, it is not feasible to cover all of the current research but only the relevant work as relates to aeronautics and space.

The report covers research in smart actuation materials, smart sensors, control of smart/intelligent structures. In smart actuation materials, piezoelectric, magnetostrictive, shape memory, electrorheological, and electrostrictive materials are covered. For sensory materials, fiber optics, dielectric loss, and piezoelectric sensors are examined. Applications of embedded sensors and smart sensors are discussed.

Control approaches for smart structures are discussed and recommendations for future research are given.

14. SUBJECT TERMS
Embedded Actuators
Embedded Sensors
Active Structures
Smart Structures and Systems
Control Systems

15. NUMBER OF PAGES
86

16. PRICE CODE
A05

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassifed	unclassified	UL